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EXPERIMENTAL QUIET ENGINE PROGRAM - SUMMARY REPORT

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16. Abstract

Two full-scale low-tip-speed fans (A & B), one full-scale high-tip-speed fan (C), scale model versions of Fans B and C, and two full-scale high-bypass-ratio turbofan engines (A and C, utilizing Fans A and C) were designed, fabricated, tested, and evaluated. Turbine noise suppression was investigated. Preliminary design studies of flight propulsion system concepts incorporating the technology features of Fans A and C, modern core engine technology, and low pressure turbine designs were used in application studies to determine acoustic-economic tradeoffs. Salient results were (1) tradeoff evaluation of fan tip speed and blade loading; (2) systematic data on source noise characteristics and suppression effectiveness; (3) documentation of high- and low-fan-speed aerodynamic and acoustic technology; (4) aerodynamic and acoustic evaluation of acoustic treatment configurations, casing tip bleed, serrated and variable pitch rotor blades, leaned outlet guide vanes, slotted tip casings, rotor blade shape modifications, and inlet noise suppression; (5) systematic evaluation of aerodynamic and acoustic effects utilizing full-size engines; (6) flyover noise projections of engine test data showing large noise reductions relative to older aircraft and significant reductions below Federal Aviation Regulations, Part 36; (7) turbine noise suppression technology development; and (8) acoustic-economic tradeoff evaluation of preliminary design high-fan-speed as opposed to low-fan-speed flight engines.

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SECTION I

SUMMARY

The NASA/General Electric Experimental Quiet Engine Program was initiated in July 1969, with the following objectives:

- Development of engine noise reduction technology
- Demonstration in engine tests of the potential benefits that this technology would have on reducing future aircraft engine noise

The Quiet Engines were physically sized in thrust output and in overall dimensions to be consistent with the propulsion systems of the older, large, four-engine aircraft of the civil transport fleet in operation at the time of initiation of the Experimental Quiet Engine Program. The noise goal of the program was the demonstration in engine tests of noise levels significantly lower (15-20 PNdB) than those of other engines.

The scope of the program encompassed the following:

- Design, fabrication, testing, and evaluation of two full-scale low-tip-speed fans (A and B) and of one full-scale high-tip-speed fan (C).
- Design, fabrication, testing, and evaluation of a number of noise control features in scale model versions of Fans B and C.
- Design, fabrication, testing, and evaluation of two full-scale high-bypass-ratio turbofan engines (A and C) representing both high and low speed fan technology.
- Design, fabrication, testing, and analysis of two core exhaust treatment configurations for suppression of turbine noise in Engines A and C.
- Preliminary design studies of flight propulsion system concepts incorporating aerodynamic and acoustic technology features of the Experimental Quiet Engine Program Fans A and C, modern core engine technology and low pressure turbine designs, and application studies of these engines in a typical conventional takeoff and landing tri-jet transport to determine acoustics/economics tradeoffs.
- Determination of the impact on airplane economics of implementing the measures necessary to reduce propulsion system noise.

The salient accomplishments of the program were as follows:

- Full-scale Fans A, B, and C were evaluated aerodynamically and acoustically,* to investigate the tradeoffs between fan tip speed and blade loading, and to provide systematic and detailed data on source noise characteristics and suppression effectiveness in conjunction with definitive aerodynamic characteristics, as well as to document high and low fan speed aero/acoustic technology to enhance the understanding for future engine design.

- A high and low fan speed, scale model program (Fans B and C) provided new data, taken under controlled aero/acoustic conditions, in the following areas of technology investigation -- location, type, and amount of acoustic treatment (B, C); casing tip bleed (B); serrated rotor blades (B); variable pitch rotor blades (B); leaned outlet guide vanes (B, C); slotted tip casing (C); rotor blade modifications (C); and inlet noise suppression (C).

- The engine test program provided important new data to improve understanding of noise reduction techniques through systematic evaluation of aerodynamic and acoustic effects.

- Application of Experimental Quiet Engine Program technology offers the following potential noise reductions relative to older four-engine aircraft and to FAR Part 36**:

Configuration	Reduction from Older Four-Engine Aircraft	Reduction from FAR-36
Low speed engine with duct wall treatment	20 EPNdB***	8 EPNdB
Low speed engine with full suppression	25 EPNdB	13 EPNdB
High speed engine with duct wall treatment and aft splitter	20 EPNdB	8 EPNdB
High speed engine with full suppression	24 EPNdB	12 EPNdB

*Aerodynamic testing of the full-scale fans was conducted in the General Electric Lynn Compressor Test Facility. Acoustic testing of the fans was conducted in the Quiet Fan Facility at the NASA-Lewis Research Center.
**Federal Aviation Regulations, Part 36, December 1969.
***Effective Perceived Noise in Decibels.

- The turbine noise suppression program provided methodology for acoustic treatment design and noise suppression prediction for jet engine turbines, identification of metallic and other treatment materials for potential use in core exhaust suppression, and techniques for measurement of turbine noise suppression.

- Preliminary design studies of two flight engines in a modern tri-jet transport aircraft showed that aircraft powered by either high or low fan speed flight engines could comply with FAR-36 requirements in treated-wall nacelle configurations, and would yield noise levels significantly below FAR-36 with fully suppressed nacelles. The economic penalties associated with the maximum feasible noise reductions (fully suppressed nacelles) were significant. At full-power, take-off noise levels between FAR-36 and FAR-36 minus 5 EPNdB, high speed fan engines in treated-wall nacelles appeared to be the most economically attractive. For noise levels below approximately FAR-36 minus 5 EPNdB to FAR-36 minus 7 EPNdB, the low speed fan engine appeared more economically attractive. However, technology being developed since the conduct of the preliminary flight engine design study and future developments may change the above relationships.

The results of the Experimental Quiet Engine Program have far-reaching significance in a number of areas. Engine noise control technology has been developed and demonstrated which will be useful in the quest for lower noise levels in aircraft of the future, so that further amelioration of the airport community noise problem can be effected. Improvements have been made in methods for prediction of noise generation, evaluation of noise reduction features, and understanding of noise generation and suppression mechanisms of various engine noise sources. The tradeoffs between fan tip speed and blade loading for quiet engines have been evaluated. The foundation has been laid for further turbine noise reduction technology by demonstration of effective high temperature core exhaust nozzle acoustic treatment. The demonstration that a high inlet flow Mach number combined with wall acoustic treatment can provide suppression equivalent to that of multiple-splitter inlets will be of significance in future inlet noise control design. The investigation of the effect of blade shape modifications on the high-tip-speed Fan C provided technology allowing important tradeoffs between aerodynamic design/performance and generated noise level. Technology has been developed and demonstrated on the effects on noise radiation of types, location, and amount of acoustic treatment.

SECTION II

INTRODUCTION

A. BACKGROUND

In July 1969, the General Electric Company, under contract to NASA, commenced work on the Experimental Quiet Engine Program with the objective of developing engine noise reduction technology and demonstrating in engine tests the integrated impact of this technology on reduction of noise. A further objective was to determine the impact on airplane economics resulting from the noise control measures required. During the Experimental Quiet Engine program, a parallel effort was conducted under contract for NASA by the Boeing Company, providing an acoustically treated, flight-type nacelle for testing on Quiet Engine A at NASA, as part of the NASA in-house program. Additional NASA testing has been conducted on both Engines A and C, and this work is continuing.

B. SCOPE OF THE EXPERIMENTAL QUIET ENGINE PROGRAM

The Experimental Quiet Engine Program had the purpose of providing the design, fabrication, and demonstration testing of engines designed with low noise production as the primary configurational constraint. The design was tempered by the additional requirements for reasonable size, weight, and operating economy. The engines were physically sized for transports which were in the commercial transport fleet at the time of initiation of the Experimental Quiet Engine Program.

A further purpose was to demonstrate noise reduction technology (by experimental testing of the engines) which, in future applications, would provide engines significantly quieter in operation than the engines powering the older, large four-engine commercial transport aircraft as well as the engines which would power the new aircraft forecast for operational service in the years after 1969. The research engines were experimental in nature. Since the purpose was demonstration of those features which reduce engine noise in operational engine systems, certain structures, components, and accessories not related to noise were not optimized in the interest of cost and availability. Such compromises did not interfere with the attainment of program objectives.

Although the initial principal thrust of the program was directed to the fan components as the principal noise sources of the engines, it was recognized that the turbine components would become important noise sources when fan noise was suppressed. Accordingly, a turbine noise suppression effort was added to the program.

As detailed below, the scope of the program encompassed the following elements:

- Design, fabrication, testing, and analysis of two full-scale low-tip-speed fans (A and B) and of one full-scale high-tip-speed fan (C).

- Design, fabrication, testing, and analysis of noise control features in scale model versions of Fans B and C.

- Design, fabrication, testing, and analysis of two full-scale high-bypass-ratio turbofan engines (A and C) designed to employ Fans A and C.

- Design, fabrication, testing, and analysis of two core exhaust treatment configurations for suppression of turbine noise in Engines A and C.

- Preliminary design studies of two high-bypass-ratio turbofan flight engines incorporating the basic noise reduction and aerodynamic technology features of the Experimental Quiet Engine Program Fans A and C, modern core engine technology, and low pressure turbine designs sized to produce 22,000 lb (97,900 N) SLS thrust, and application studies of these engines in a typical CTOL tri-jet transport to determine acoustics/airplane economics tradeoffs.

Figure 1 presents an overall schedule and outline of the major elements of the Experimental Quiet Engine Program.

The Phase I design effort entailed a six-month effort for definition of full-scale fans, scale model fans and engine designs, and ordering of long-lead-time hardware.

In the full-scale fan program, two low speed fans (A and B) and one high speed fan (C) were designed and fabricated, and aero/mechanical testing was conducted at the GE-Lynn Full-Scale Fan Test Facility. Each fan was subsequently shipped to NASA for acoustic evaluation to investigate the tradeoffs between fan tip speed and blade loading, as well as the effects of numbers of blades.

The half-scale fan program evaluated a number of concepts for source noise reduction, as well as acoustic treatment, using scale model Fans B and C. While the primary emphasis was directed to acoustic investigations, aerodynamic evaluation of the acoustic concepts was essential. Concepts evaluated were as follows:

- The effects on acoustic and aerodynamic characteristics of location, type, and amount of acoustic treatment with half-scale Fans B and C.

- The effects of inlet casing tip bleed, serrated rotor blades, leaned outlet guide vanes, and variable pitch rotor blades with half-scale Fan B.

- The effects of leaned outlet guide vanes, slots in the casing over the fan rotor blade tips, variations in rotor blade profile shapes, and a series of inlet suppression configurations (including acoustically treated splitters and high throat Mach numbers) with half-scale Fan C.

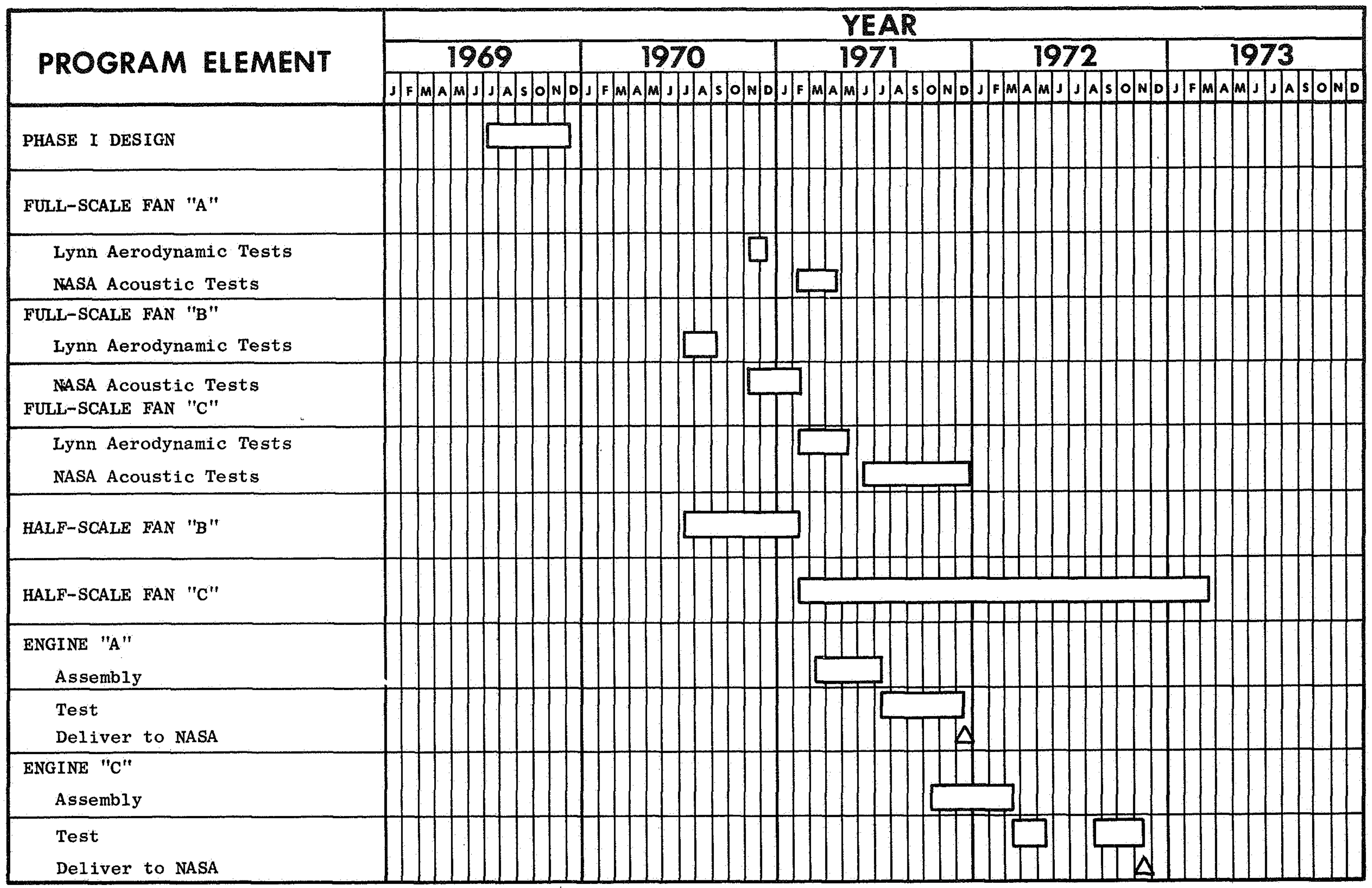

Figure 1. Schedule of Major Program Elements.

The engine program entailed design, fabrication, and testing of two full-scale engines - Engine A (low-tip-speed fan) and Engine C (high-tip-speed fan). Each engine was evaluated acoustically and for related aero/thermodynamic performance characteristics at the Peebles, Ohio test facility. A variety of suppression concepts was also evaluated on each engine. Suppression concepts evaluated on Engine A included acoustically treated fan inlet and exhaust duct splitters, core engine exhaust duct treatment, variations in inlet duct length, thick lip inlet and thin lip, blow-in door inlet, acoustically wrapped external casings, and various combinations of these. Suppression concepts evaluated on Engine C included acoustically treated fan inlet and exhaust duct splitters, core engine exhaust duct treatment, variations in inlet duct length, multiple pure tone inlet treatment, coplanar exhaust nozzles, and various combinations of these.

In the turbine noise suppression programs, high temperature acoustic treatment was developed for the core engine exhausts of Engines A and C. Special tests were performed on both engines to evaluate turbine noise suppression.

The flight engine design study comprised definition of preliminary designs of high and low fan speed, high-bypass-ratio turbofan engines, based on the technology developed during the Experimental Quiet Engine Program. The two preliminary design engines were applied to a typical CTOL tri-jet transport aircraft to evaluate noise/airplane economics tradeoffs.

The purpose of this report is to summarize the most important results of the Experimental Quiet Engine Program, while providing references for more complete details of design and test results.

SECTION III

ENGINE AND COMPONENT DESIGN

A. DESIGN OBJECTIVES

The design effort encompassed the design of three full-scale fans, each containing low-noise design features. The three fan designs spanned a range of tip speed and aerodynamic loading of interest and, with the TF39/CF6 core and selected low pressure turbines, provided three possible bypass fan engine designs. The TF39/CF6 core was selected to provide both minimal risk and a reliable gas generator.

Based upon preliminary engine cycle analyses, the three fan designs were selected with pressure ratios of 1.5 for Fans A and B and 1.6 for Fan C.

The fans were designed for maximum interchangeability of components between the General Electric-Lynn full-scale fan test facility, the NASA-Lewis Acoustics Facility, and the full-scale experimental engines.

The low pressure turbine designs were selected to match the fan requirements. The first four stages of the five-stage CF6 low pressure turbine were designed to drive Fans A and B. A new high-loading, low pressure turbine design was selected for Fan C.

Inlets selected for testing included standard reference bellmouths as well as two flight-type inlets (thick lip and thin lip types). The inlet and exhaust systems were aerodynamically designed to be representative of typical aircraft applications.

This section of this report summarizes engine and component design of Phase I of the overall program, and accordingly, provides design intent. Full details of the design are given in References 1 and 2, including drawings and hardware photographs. Subsequent modifications to fans, such as acoustic treatment configurations, are discussed in Section IV of this report.

Figures 2 and 3, respectively, show cross sections of Quiet Engines A and C. The options for selecting the two engines were kept open until aerodynamic and acoustic evaluation of the three fans was completed. Designs were completed for Engines A, B and C, and A and C were finally selected for construction to provide one high and one low speed fan experimental engine. The full-scale fan performance testing (See Section IV.A.1.a) showed that Fan A had the highest performance of the three fans. The full-scale fan acoustic testing (See Section I.V.A.1.b) showed that Fan A had a slight acoustic advantage [lower 200-foot (61-m) sideline maximum PNL's in the dominant aft quadrant] over Fan B. Accordingly, Fan A was chosen as the basis for the low-fan-tip-speed engine. Fan C provided the basis for the high-fan-tip-speed engine. Figures 4 and 5 show the resulting engine hardware.

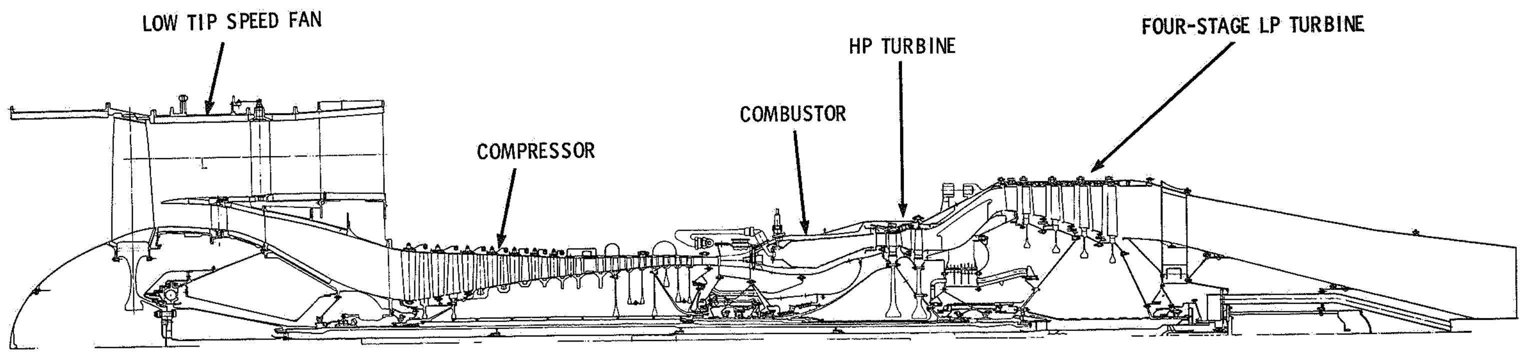

Figure 2. Layout Drawing of Engine A.

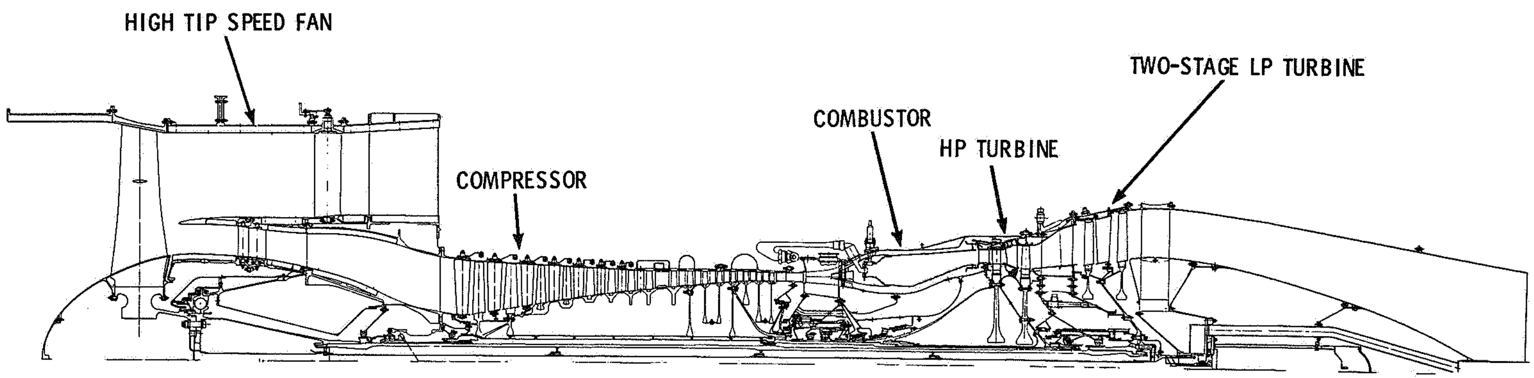

Figure 3. Layout Drawing of Engine C.

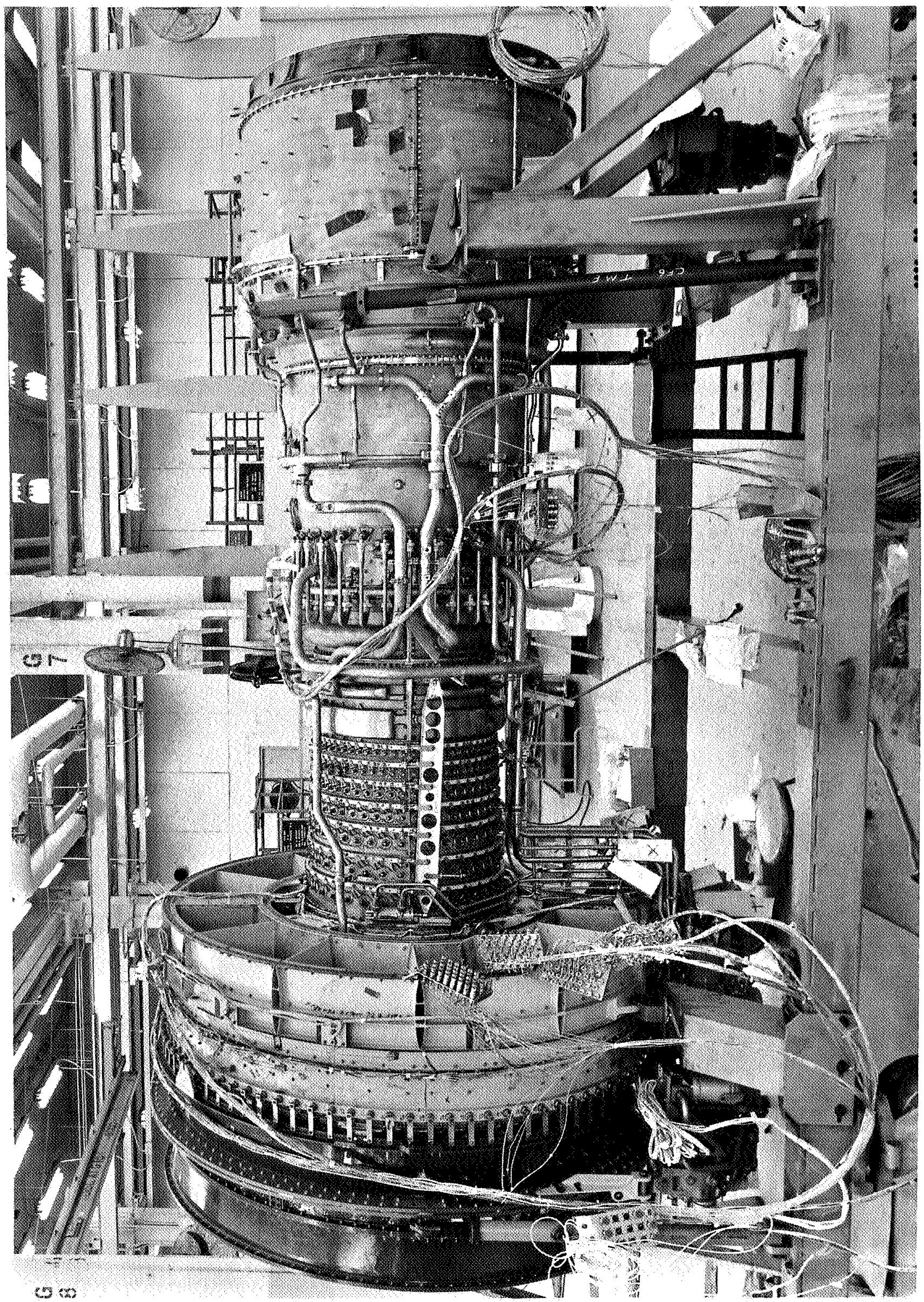

Figure 4. Engine A.

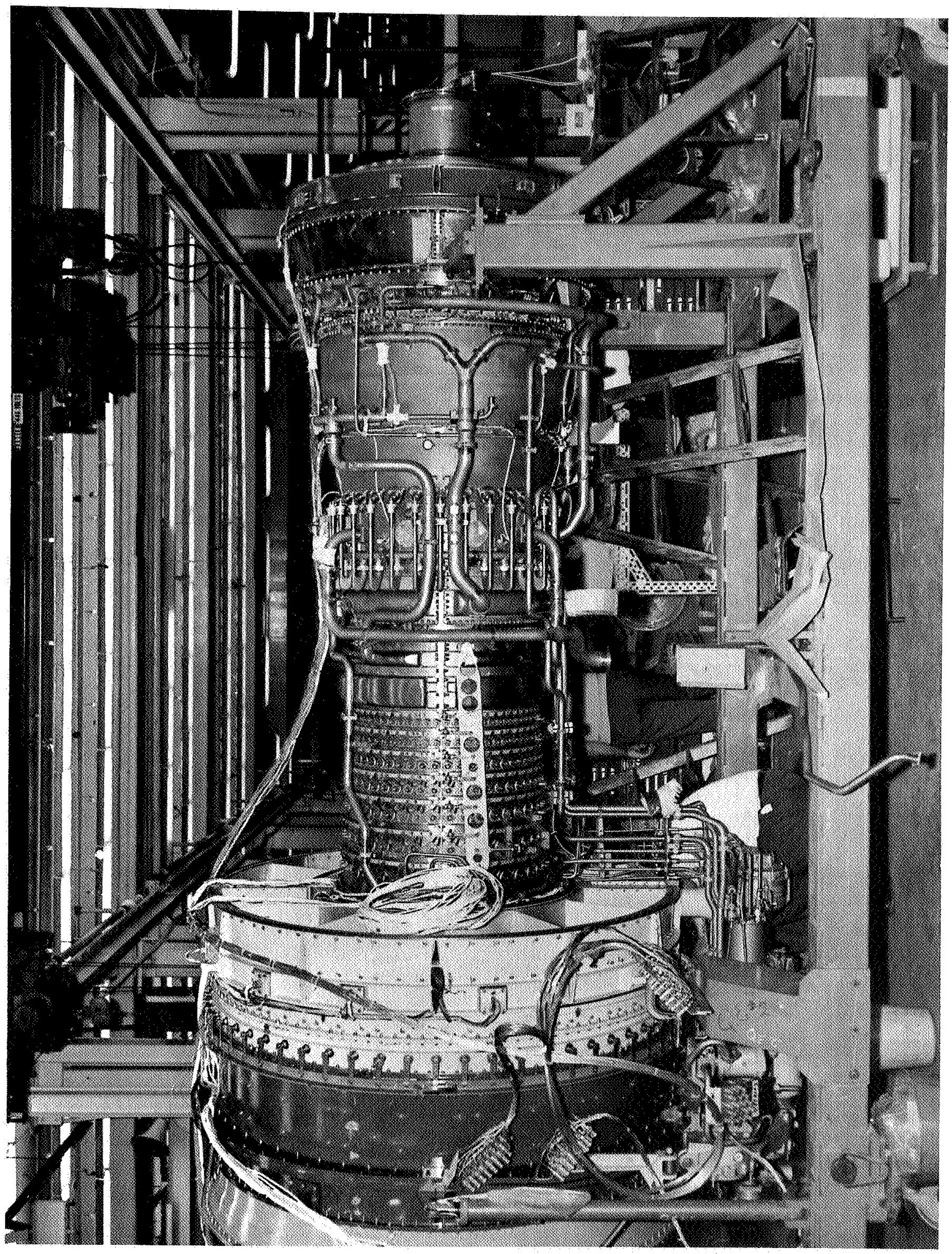

Figure 5. Engine C.

B. FAN DESIGN

1. Fan Acoustic Design

a. Basic Fan Design Considerations

Analytical studies have shown that, by reducing the fan aerodynamic loading, a significant reduction in blade passing frequency noise can be obtained (See Reference 3). The lower loading can be achieved by lowering fan pressure ratio and increasing fan size in order to maintain thrust, or by increasing fan tip speed while maintaining the same design pressure ratio. The former method requires a larger diameter nacelle for a given thrust level, but provides an inherently lower noise source. The latter method permits a smaller diameter nacelle and a lower number of low pressure turbine stages for a given thrust level.

The increased tip speed does increase broadband noise generation and does accentuate the supersonic phenomenon of multiple pure tones (MPT's). The MPT's are known to occur when the fan rotor tip relative Mach number exceeds unity. MPT-dominated frequencies are characteristically well below the blade passing frequency and at multiples of the shaft revolutions of the fan rotor. These tones may be controlled by keeping their frequency low (i.e., in the low-annoyance frequency range). This is best achieved by keeping blade number and/or fan rotor rpm as low as possible. Thus, by judicious selection of fan pressure ratio, fan size, and tip speed, a viable low noise fan design can be obtained based on either low or high tip speed.

Two basic fan designs were selected for the Experimental Quiet Engine Program; one at a design tip speed of 1160 ft/sec (353.6 m/sec) and another at 1550 ft/sec (472.4 m/sec), with each engine developing 4900 pounds (21,800 N) of thrust at the altitude cruise design point.

b. Blade Row Spacing

Both analytical and experimental studies have shown the advantages of wide rotor/OGV spacing in producing low noise fans. Thus, it is known that there is considerable gain in going to 2.0-rotor aerodynamic chord spacing, with a diminishing gain beyond 2.0 chords (See Reference 4). Due to the small gain obtained in going beyond two-chord spacing and the mechanical problems resulting from such wide spacing, all three fans were designed to have their rotor/stator spacing set at two rotor aerodynamic chords.

c. Vane and Blade Number Selection

The selection of the number of blades and vanes is intimately connected with both noise generation and its psychoacoustic effects. The number of blades and the rotational speed of the fan determine the blade passing frequency and its harmonics. Therefore, one of the design considerations was to place the pure tones in frequency bands where annoyance levels are low. The ratio of the number of blades and vanes has been shown to have an appreciable effect on the pure tone noise levels. In general, a vane/blade ratio in excess of two permits a lower noise design. Higher vane/blade ratios can result in still lower noise; however, there is a diminishing return, and serious aeromechanical design problems arise when excessively high vane numbers are employed (See Reference 5). Accordingly, the ratio of numbers of vanes to blades was selected at 2.25 for Fan A and at 2.31 for Fans B and C.

2. Acoustic Treatment Design

Fan frame acoustic treatment was designed for placement in the Experimental Quiet Engine fan flow passages and in the inlet of the core engine compressor passage. In each case, it was desired to have a broadband absorption characteristic (at both approach and take-off power settings) centered at different peak frequencies. Therefore, a multiple-degree-of-freedom resonator treatment was selected. Reference 1 gives full information on the acoustic treatment design. Sections IV and V of this report discuss use of acoustic treatment in the fan and engine test programs.

3. Fan Aerodynamic Design

The aerodynamic design point for the three fans was selected at the altitude cruise condition, 0.82 Mach number at an altitude of 35,000 feet (10.67 km). This selection reflects the desire to maximize fan efficiency at the flight condition where the majority of the fuel would be consumed. Aerodynamic design point characteristics for the three fans are presented in Table I.

Table I. Design Characteristics for Fans A, B, and C.

Design Characteristic	Fan A	Fan B	Fan C
Corrected Tip Speed, ft/sec (m/sec)	1160 (354)	1160 (354)	1550 (472)
Fan Bypass Pressure Ratio	1.50	1.50	1.60
Fan Core Pressure Ratio	1.32	1.43	1.49
Corrected Airflow, lb/sec (kg/sec)	950 (431)	950 (431)	915 (415)
Flow/Annulus Area, lb/sec ft^2 (kg/sec m^2)	41.3 (202)	41.3 (202)	4.13 (202)
Inlet Hub-Tip Radius Ratio	0.465	0.465	0.360
Tip Diameter, in. (m)	73.35 (1.863)	73.35 (1.863)	68.30 (1.735)
Bypass Ratio	5.6	5.5	5.0

The design rotor tip relative Mach number was supersonic for all three fans. In the supersonic region the rotor blades employed profile shapes which, based on past experience, minimized excessive shock losses on the suction surface and still were compatible from a throat area and energy addition standpoint. The blade meanline shapes and points of maximum thickness varied radially and were blended to shapes that are similar to a double circular arc profile in the hub region. Profile shapes at other radii were generally similar in appearance to the NASA multiple-circular arc profiles.

The profile shapes for the bypass OGV's which operate at moderate conditions of inlet Mach number and diffusion factor, were designed with a modified NASA 65-series thickness distribution on a circular arc meanline. In the case of the core, Fan A OGV's incorporated the same basic airfoil series. Fan B and Fan C core OGV's, which operate in a relatively high inlet Mach number environment when considering the turning requirement and diffusion factor level, employed a tandem vane row wherein the profile shapes were specifically tailored to minimize suction surface Mach numbers and, therefore, prevent shock losses and minimize diffusion losses.

Additional information on the details of the fan designs is contained in Reference 1.

4. Fan Mechanical Design

The basic design features of the three fans are as follows:

- Fan A - Low tip speed, high aspect ratio, 40 tip-shrouded blades

- Fan B - Low tip speed, low aspect ratio, 26 cantilevered blades

- Fan C - High tip speed, high aspect ratio, 26 blades with a mid-span shroud*

Figures 6, 7 and 8 show the three full-scale fan rotors. Additional information on the fan mechanical designs is given in Reference 1.

C. CORE ENGINE DESIGN

1. Basis of Core Engine Design

The core engine or basic gas generator for the three possible engines of the program was representative of the proven core used in the General Electric TF39 and CF6 turbofan engines. The core engine was actually oversized for this application, and this was done to minimize risk without compromising the results.

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* As part of the performance evaluation, the outer blade panels were recambered and the resulting configuration issued as "Mod I". A "Mod II" configuration was also issued, in which the mid-span dampers were removed and additional blade reshaping was incorporated. This configuration is shown in Figure 8.

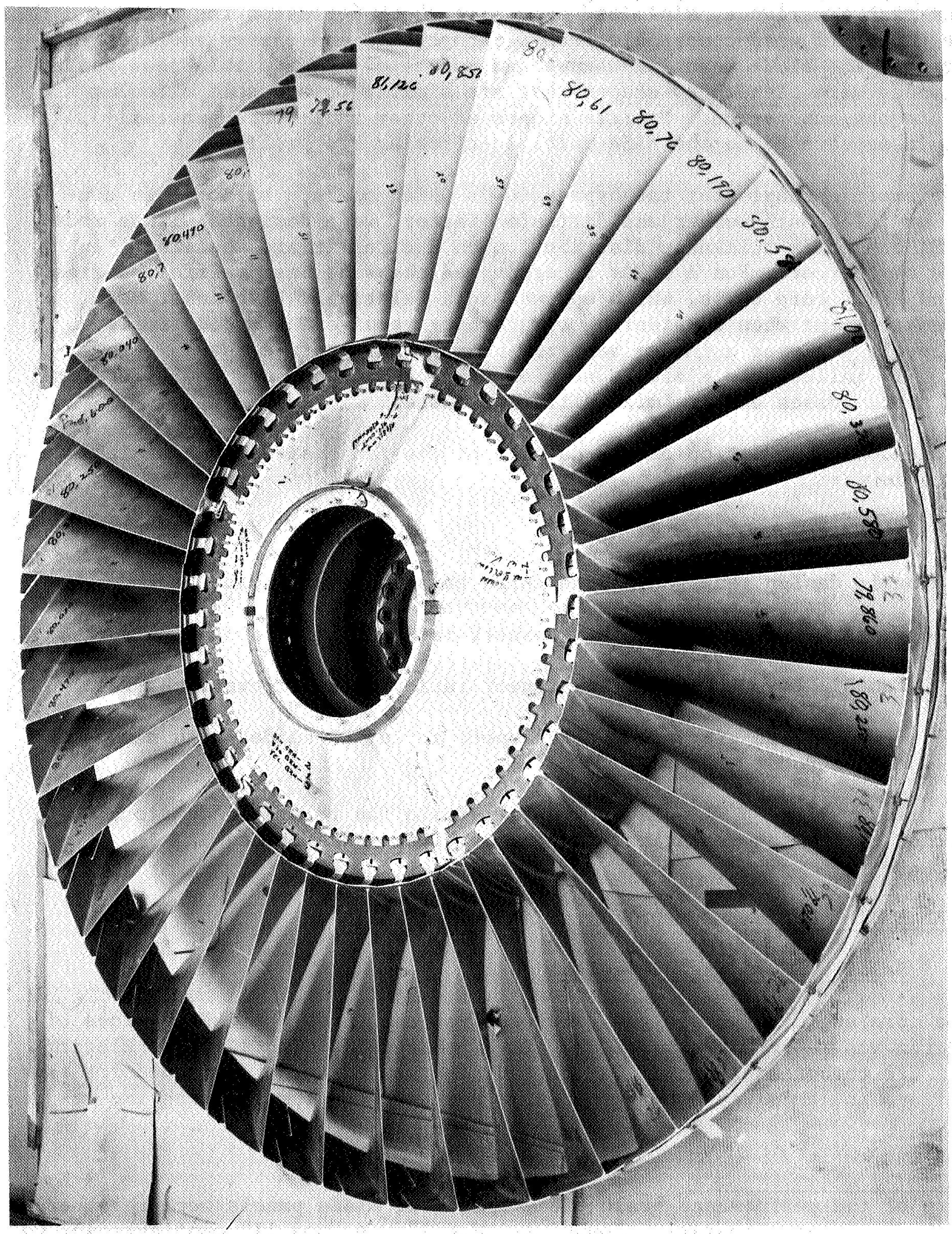

Figure 6. Full-Scale Fan Rotor A.

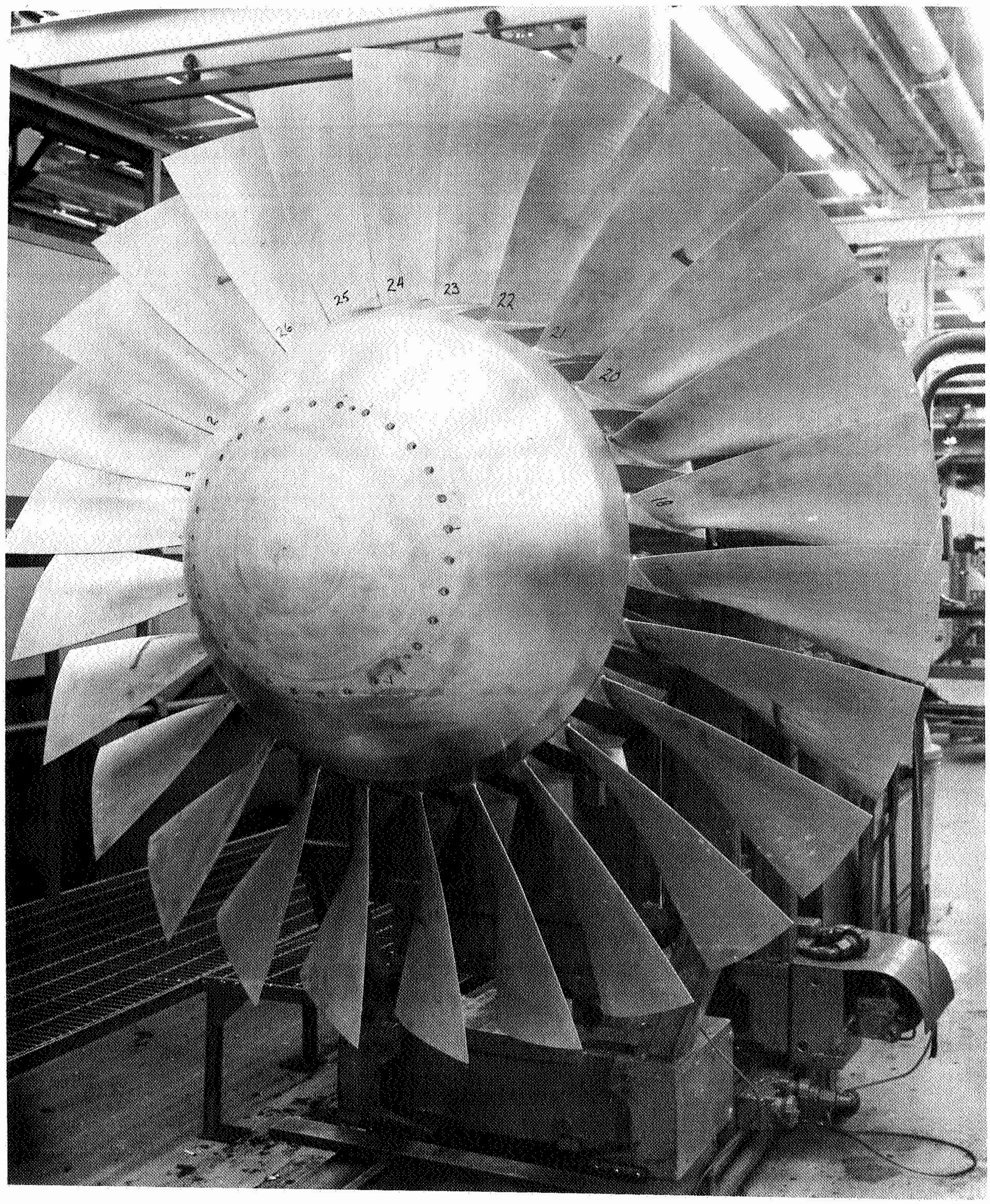

Figure 7. Full-Scale Fan Rotor B.

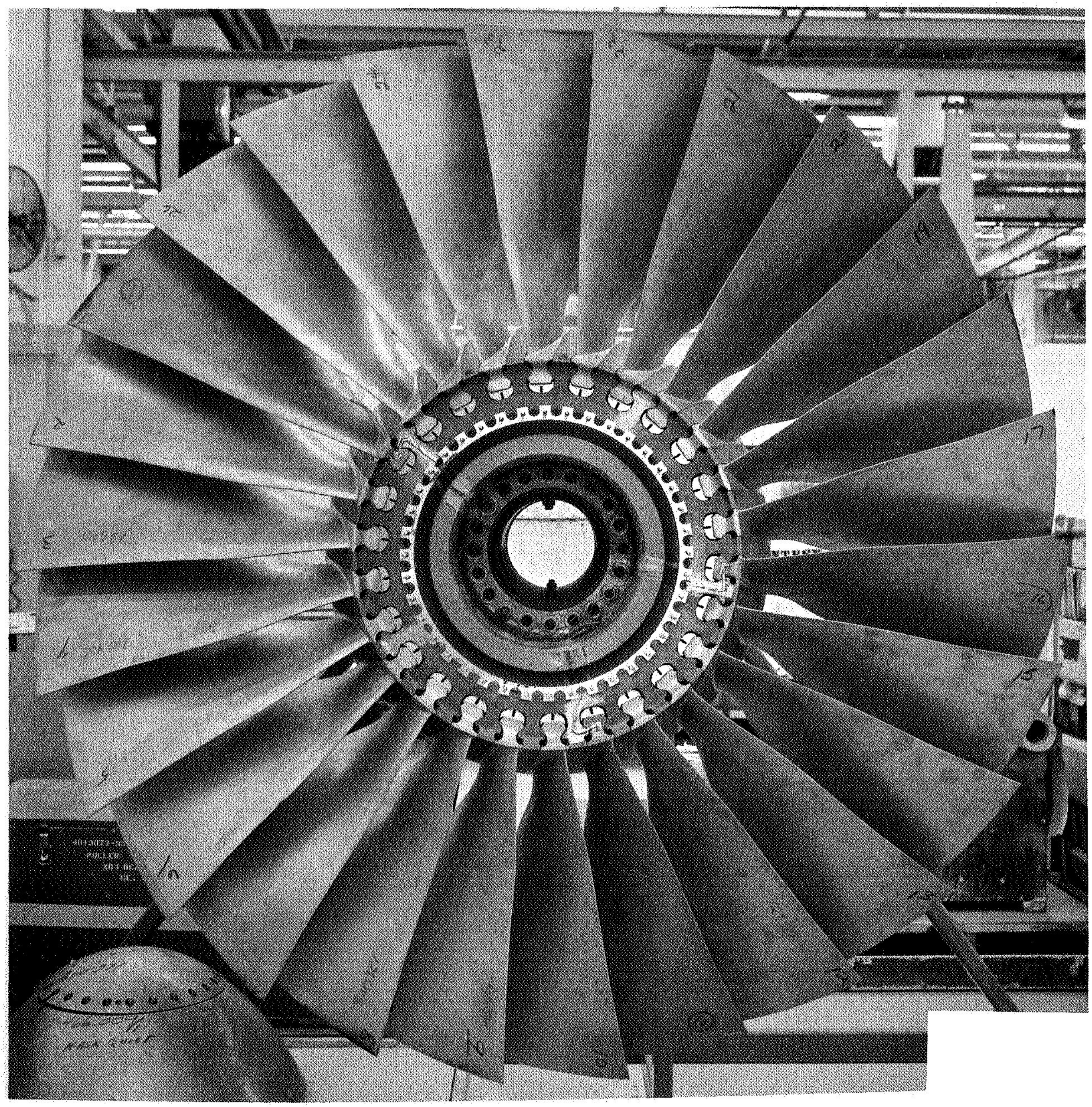

Figure 8. Full-Scale Fan Rotor C.

2. Compressor Design

The TF39/CF6 compressor provided the efficiency, stall margin, and distortion tolerance required for the experimental engines employed in this program. It was a single-spool, 16-stage, variable stator design of 17.5 pressure ratio and a nominal design corrected airflow of 142.5 lb/sec (64.6 kg/sec) (See Figure 9).

3. Combustor Design

The combustor was the CF6 commercial engine low smoke combustor with minor modification of the fuel nozzles to reflect the reduced fuel flow requirements (See Figure 10).

4. High Pressure Turbine Design

The two-stage high pressure turbine was similar to the design used in the TF39 and CF6 engines, except for differences due to the lower temperature and lower pressure levels of the Quiet Engine (See Figure 11).

D. LOW PRESSURE TURBINE DESIGN

1. Engines A and B

The Engines A and B low pressure turbine rotor used the first four stages of the CF6 five-stage low pressure turbine rotor. The turbine aerodynamic design requirements were determined by the power and speed requirements of the fan and by the need to hold a relatively low tip diameter to obtain an optimum boattail angle on the cowl aft of the fan discharge. Coupled with this was a high efficiency level for engine cycle matching. The result was a low-tip-speed turbine, utilizing 4 stages for optimum power extraction and efficiency. The turbine was derived by removing the last stage from the 5-stage CF6 LP turbine which, in conjunction with flow area changes, produced a low stage loading which, together with the relatively low tip speed, resulted in an inherently low-stressed and efficient design (See Figure 12).

2. Engine C

The Engine C low pressure turbine was a new two-stage design. The turbine aerodynamic design requirements were determined by the power and speed requirement of Fan C and by the design intent to minimize the radial offset of the flowpath between the HP and LP turbines such as found in Engines A and B. Aerodynamic details were selected to provide a high efficiency level for best engine cycle matching. The result was a well-balanced, low-tip-speed, two-stage turbine. This resulted in a pitch loading on the first stage of 1.47 and an overall average turbine loading of 1.035. The exit Mach number was set at 0.406, which was consistent with current design practice, with an exit swirl angle of about one degree at design (See Figure 13).

The low pressure turbine design data for Fan C at the SLS maximum-power operating condition are shown in Table II. Mechanical design considerations are given in Reference 1.

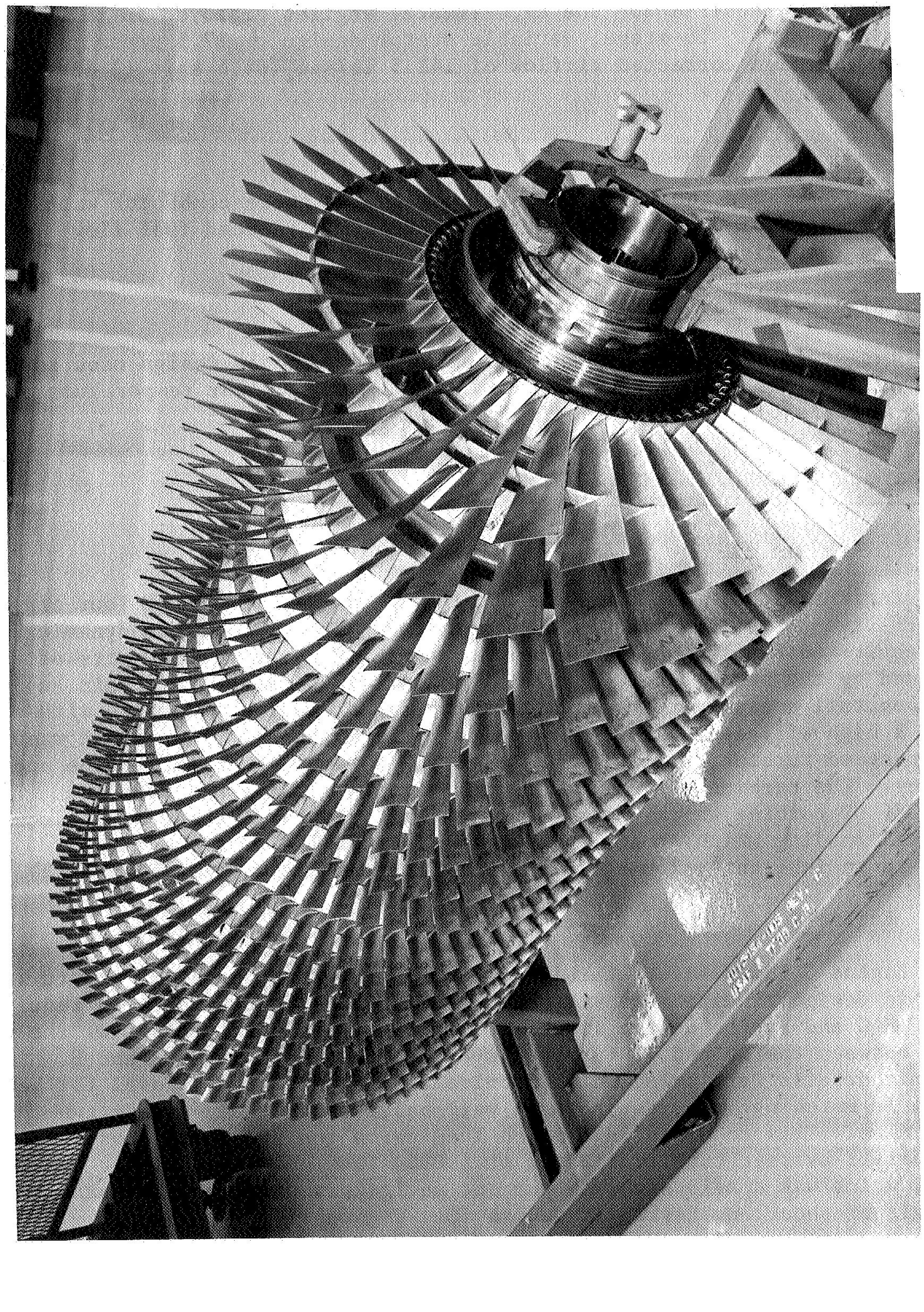

Figure 9. Compressor Rotor.

Figure 10. Combustor.

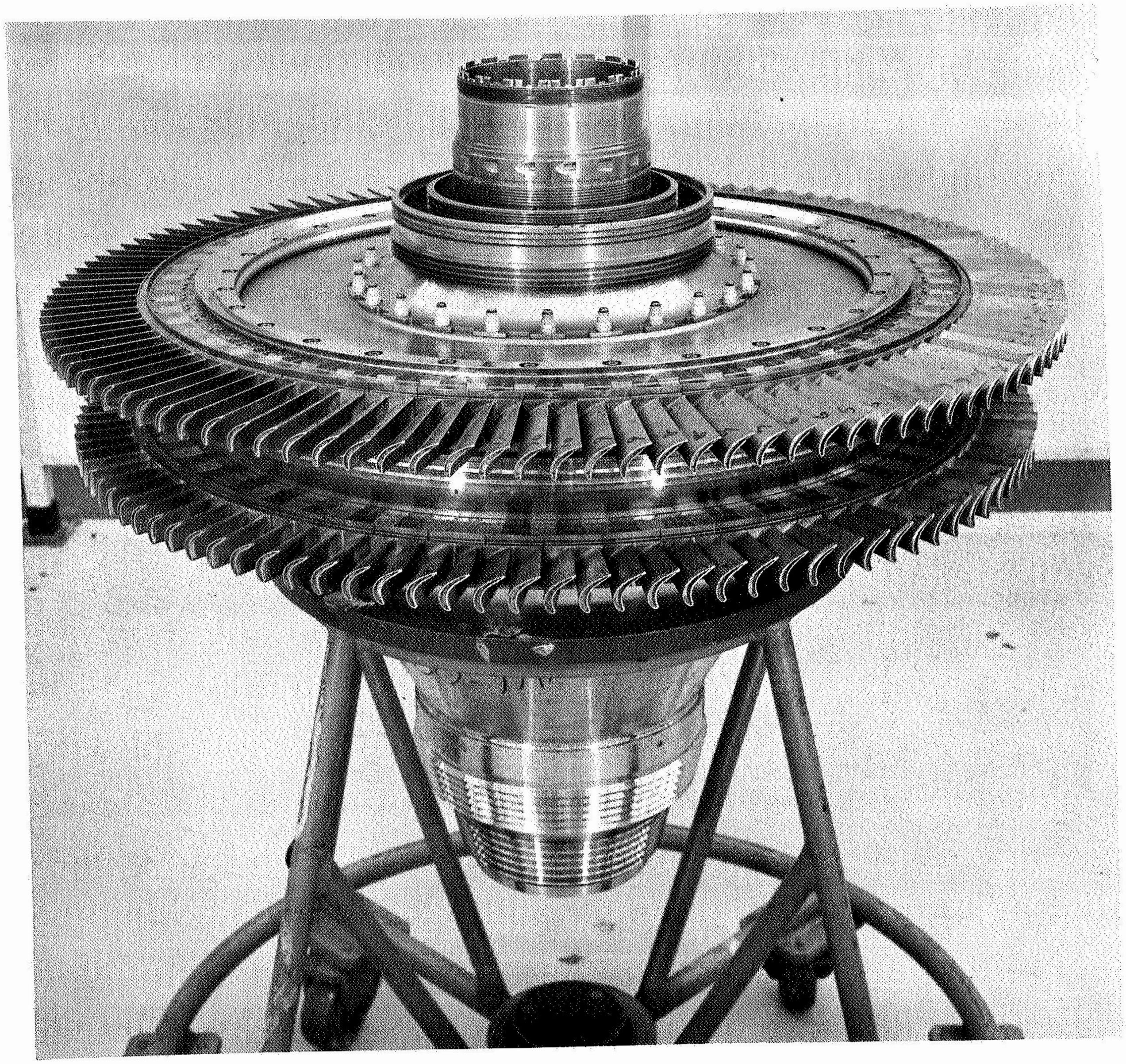

Figure 11. High Pressure Turbine Rotor.

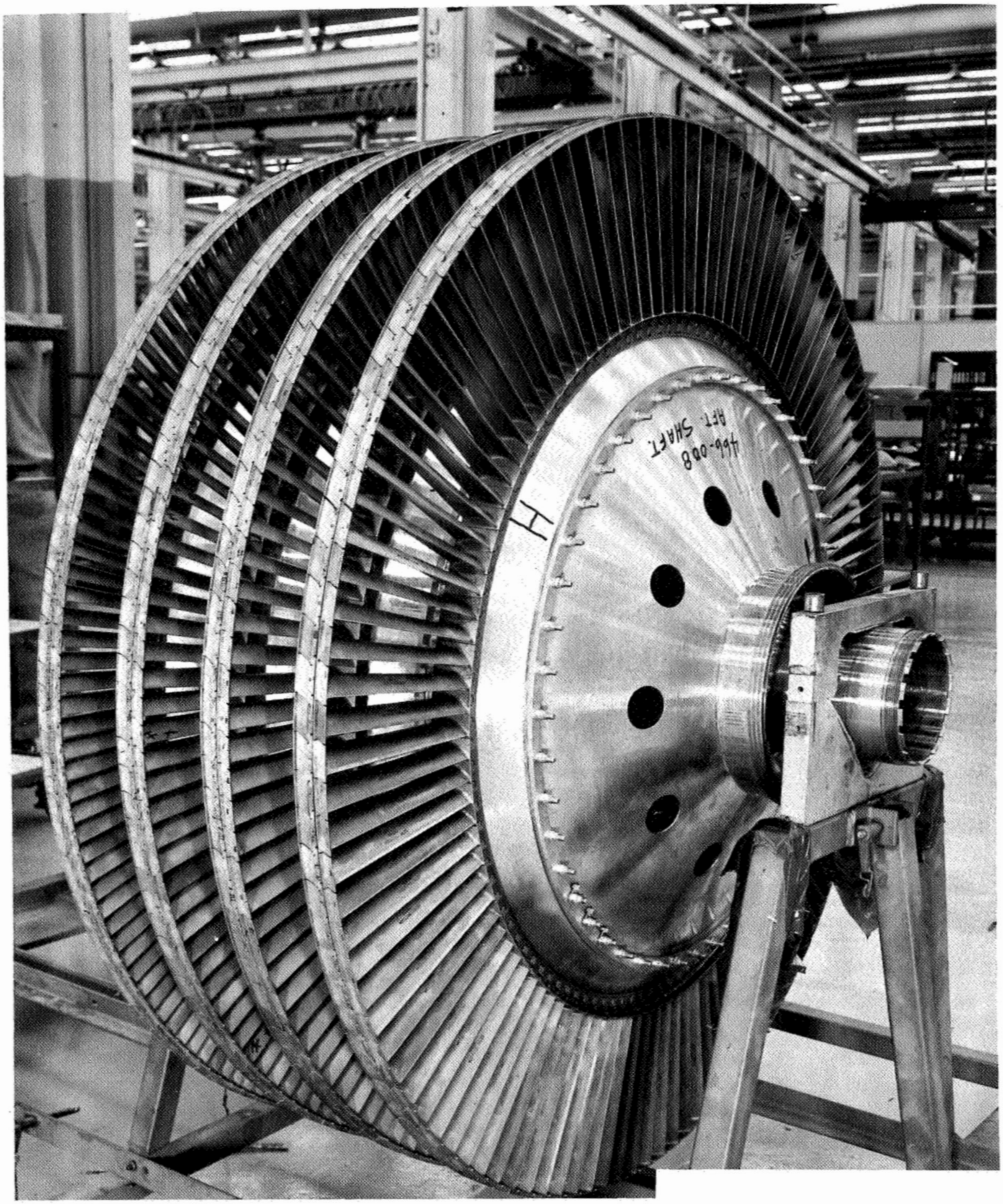

Figure 12. Low Pressure Turbine Rotor A.

Figure 13. Low Pressure Turbine Rotor C.

Table II. Design Data, Low Pressure Turbine for Engine C, Maximum Power Operating Condition, Sea Level Static.

Parameter	Stage 1 Diameter ID	Stage 1 Diameter OD	Stage 2 Diameter ID	Stage 2 Diameter OD	Total Turbine
VANES					
Exit diameter, inches (m)	29.78 (0.756)	40.88 (1.038)	31.00 (0.787)	43.91 (1.115)	---
Number	60		120		---
Inlet angle	0	0	52.29	42.84	---
Exit angle	73.28	67.60	62.24	53.30	---
Inlet pressure, psia (kg/m^2)	54.3 (38,170)		27.3 (19,190)		---
Inlet temperature, ° R (° K)	1661 (923)		1425 (792)		---
BLADES					
Exit diameter, inches (m)	30.35 (0.772)	42.26 (1.073)	31.50 (0.800)	45.00 (1.143)	---
Number	118		130		---
Inlet angle	67.57	45.33	44.67	0	---
Exit angle	65.37	65.38	43.12	52.81	---
Exit Mach no.	0.542		0.406		---
Exit swirl angle	47.2		1.3		---
STAGE					
Shaft work, Btu/lb (joules/kg)	64.4 (149,800)		31.2 (72,570)		95.6 (222,400)
Blade velocity, pitch, U_p ft/sec (m/sec)	745 (227)		785 (239)		---
Loading, $gJ\Delta h/2U_p^2$	1.470		0.641		1.035
Turbine efficiency	0.892		0.904		0.903

Note: all angles measured from axial direction, in degrees.

E. ENGINE SYSTEM

1. Engine Cycle Performance

This section summarizes overall Engine A, B, and C performance data, based on:

- Full-scale fan test results of Fans A, B, and C
- Predicted low pressure turbine performance maps determined under Phase I of the Experimental Quiet Engine design
- Measured core engine performance
- SLS testing of Engines A and C

Performance data are shown in Table III. Fan duct pressure losses representative of predicted values and tailpipe pressure losses substantiated by test on Engine A are included. The fuel heating value used was 18,400 Btu/lb (42,800 joules/kg). Bleed airflow and power extraction are not represented in the base data shown.

The three engines were sized for 4900 pounds (21,800 N) thrust at the engine design point, Mach 0.82, 35,000 feet (10,668 m). Fans A and B had approximately the same fan pressure ratio and airflow at this flight condition. Fan C, which had a higher fan pressure ratio commensurate with its higher fan tip velocity, was sized for a smaller airflow. At the design point, the difference in specific fuel consumption was less than 3 points, with the Fan A cycle having the lowest level at the cruise condition. The low core exhaust nozzle pressure ratio and exhaust velocity of Engine C was a direct result of increasing the core exhaust nozzle area, inherent in the design of this engine.

With the engines sized at the Mach 0.82, 35,000-foot (10,668-m) flight condition, the performance at sea level static was established by operation to a thrust level of 22,000 pounds (97,900 N). At this condition, the fan and core speeds were reduced from the cruise levels and the cycle pressure ratio rematches at a lower level.

Performance at the take-off condition of Mach 0.25, sea level, was established by holding the core gas generator speed constant at the level defined by the sea level static thrust condition.

2. Engine Installation Aerodynamics

a. Fan Bypass Duct and Nozzle Aerodynamic Design

The fan bypass duct and nozzle comprise the region of fan exhaust from the outlet guide vanes to the exit of the duct. Surfaces were defined to maintain a smoothly varying flow area. Duct flow areas were sized to give Mach numbers of the order of 0.5 over the major portion of the duct. Mach

Table III. Quiet Engine Cycle Performance Data for Engines A, B, and C.

Parameter	Mach 0.82, 35,000 ft (10,668 m)* Standard Day			Sea Level Static Standard Day			Mach 0.25 Sea Level Standard Day		
	A	B	C	A	B	C	A	B	C
Net thrust†, lbs (N)	4900 (21800)	4900 (21800)	4900 (21800)	22000 (97900)	22000 (97900)	22000 (97900)	16046 (71380)	16134 (71770)	16013 (71230)
Specific fuel consumption, hr^{-1}	0.645	0.652	0.673	0.360	0.367	0.382	0.475	0.483	0.504
Total airflow, lb/sec (kg/sec)	379 (171.9)	377 (171.0)	364 (165.1)	833 (377.9)	829 (376.1)	808 (366.5)	864 (391.9)	863 (391.5)	831 (377.0)
Total corrected airflow, lb/sec (kg/sec)	961 (435.9)	957 (434.1)	923 (418.6)	833 (377.9)	829 (376.1)	808 (366.5)	833 (377.9)	831 (377.0)	800 (362.9)
Bypass ratio	6.14	5.93	5.31	5.75	5.57	4.99	5.96	5.78	5.14
Fan pressure ratio	1.49	1.48	1.66	1.40	1.40	1.50	1.38	1.38	1.47
Duct exhaust nozzle pressure ratio	2.29	2.27	2.55	1.39	1.38	1.49	1.42	1.42	1.52
Duct exhaust velocity, ft/sec (m/sec)	1010 (307.8)	1009 (307.5)	1031 (314.2)	788 (240.2)	783 (238.6)	875 (266.7)	821 (250.2)	817 (249.0)	903 (275.2)
Cycle pressure ratio	16.80	17.20	18.31	14.74	15.11	16.22	14.14	14.52	15.54
Turbine inlet temp., T_4, ° F (° C)	1811 (988)	1808 (987)	1784 (984)	1951 (1066)	1961 (1072)	1940 (1061)	1931 (1055)	1942 (1061)	1920 (1049)
Core exhaust nozzle pressure ratio	1.97	2.05	1.50	1.35	1.38	1.18	1.35	1.38	1.18
Core exhaust velocity, ft/sec (m/sec)	1587 (483.7)	1589 (484.3)	1239 (377.7)	1174 (357.9)	1220 (371.9)	862 (262.7)	1177 (358.8)	1222 (372.5)	862 (262.7)

† Uninstalled net thrust, based on ideal exhaust nozzle performance.

*Cruise Design Condition.

numbers at the entrance to the duct which were representative of the Mach numbers that exist over most of the duct were 0.504, 0.490, and 0.491 for Engines A, B, and C, respectively, at sea level static take-off; and 0.585, 0.569, and 0.534, respectively, at 0.82 Mach number, 35,000 foot (10,668 m) altitude cruise.

b. Core Duct and Nozzle Aerodynamic Design

The core nozzle exit areas of both test engines were increased prior to test compared to the original design values for the purpose of reducing jet noise. The core nozzle area on Engine A was increased from 552 to 577 in^2 (0.356 to 0.372 m^2). The resulting exhaust velocity on Engine A at SLS take-off was 1174 fps (357.9 m/sec). The core nozzle on Engine C was designed to minimize the jet noise contribution to overall noise, since the new low pressure turbine required special attention. The area was increased from 678 to 850 in^2 (0.437 to 0.549 m^2), resulting in an exhaust velocity at SLS take-off of 862 fps (262.7 m/sec).

c. Aircraft Pylon and Lower Pylon Fairing Aerodynamic Design

The aircraft structural pylon fairing and the lower pylon fairing (used for accessory drive shaft and pneumatic, hydraulic, and electrical lines) were designed to the same aerodynamic criteria (common leading edge). The lower pylon fairing was closed smoothly from the maximum width so that the trailing edge occurred at the fan nozzle exit.

SECTION IV

TEST AND EVALUATION

A. FAN AERO/ACOUSTIC TESTING

1. Full-Scale Fan Testing

a. Aerodynamic Performance Evaluation

(1) Test Setup and Procedure

Performance tests of the three fan components were made in General Electric's Large Fan Test Facility at Lynn, Massachusetts. The facility and the performance instrumentation are described in References 6 through 8.

(2) Performance of Fan A

The Fan A test vehicle is shown in Figure 14. This represents the configuration utilized throughout the program involving Fan A (see Reference 3).

The data below present the overall fan performance in the form of two maps to distinguish the performance characteristics in the fan bypass and fan core regions. One map presents fan bypass total-pressure ratio and efficiency versus total fan flow. The second map presents fan core total-pressure ratio and efficiency versus fan core flow.

Fan A was designed to deliver a bypass total-pressure ratio of 1.50 at a total fan flow of 950 lb/sec (430.9 kg/sec). The design bypass adiabatic efficiency was 86.5%. The peak adiabatic efficiency at design speed was 88.5% at a bypass pressure ratio of 1.505 and a total fan flow of 970 lb/sec (440.0 kg/sec).

A bypass total-pressure ratio of 1.52 and an adiabatic efficiency of 88.3% at a total flow of 962 lb/sec (436.4 kg/sec) were achieved in the test program. The fan core region was designed to develop a total-pressure ratio of 1.32 at a flow of 144.0 lb/sec (65.3 kg/sec). A fan core pressure ratio of 1.356 was achieved at its design flow, and at this condition, a fan core adiabatic efficiency of 83.1% was measured.

The operational limit line was determined up to 100% corrected speed. Rotating stall was the operational limit at all speeds except 100% where high bypass OGV stress precluded further increases in back pressure. At 100% corrected speed, an operating margin of 12.4% was achieved relative to the design operating line at altitude-cruise conditions. At 90% corrected speed the operating margin was 10.8% relative to the design operating line at sea-level-static conditions. The measured performance of Fan A is shown in Figures 15 and 16.

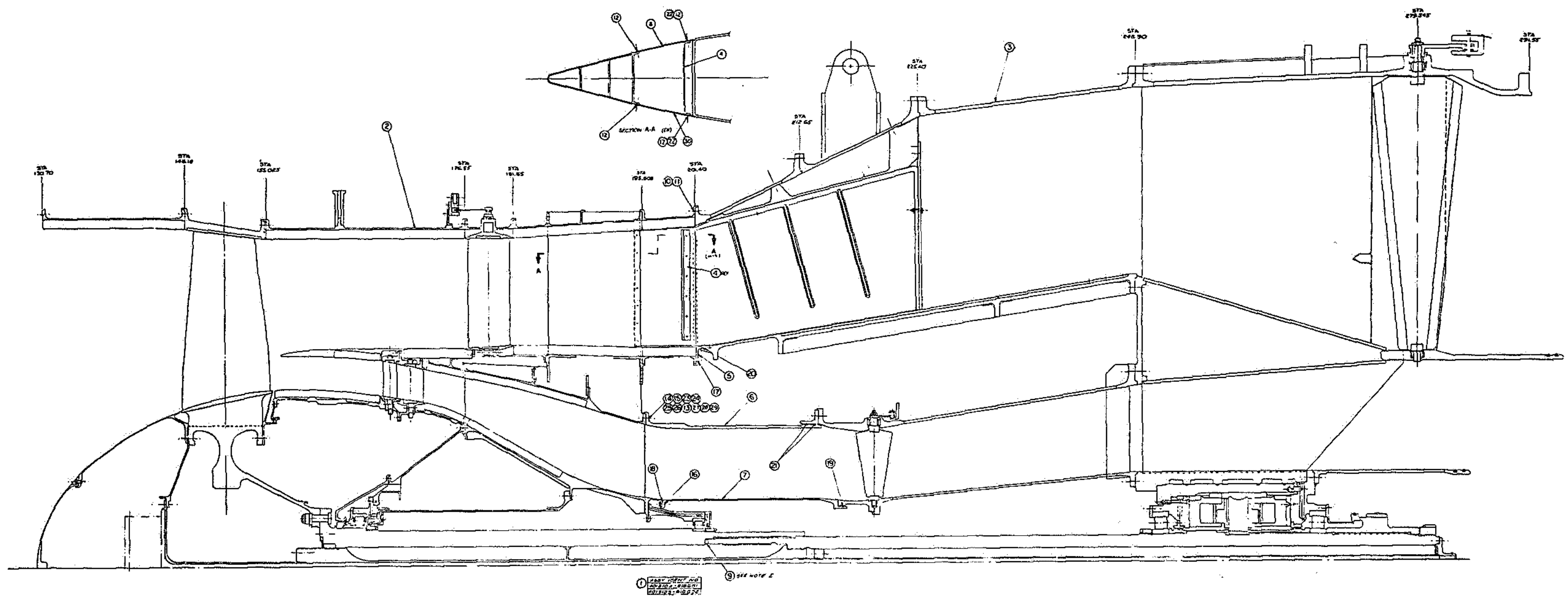

Figure 14. Fan A Component Test Vehicle Layout.

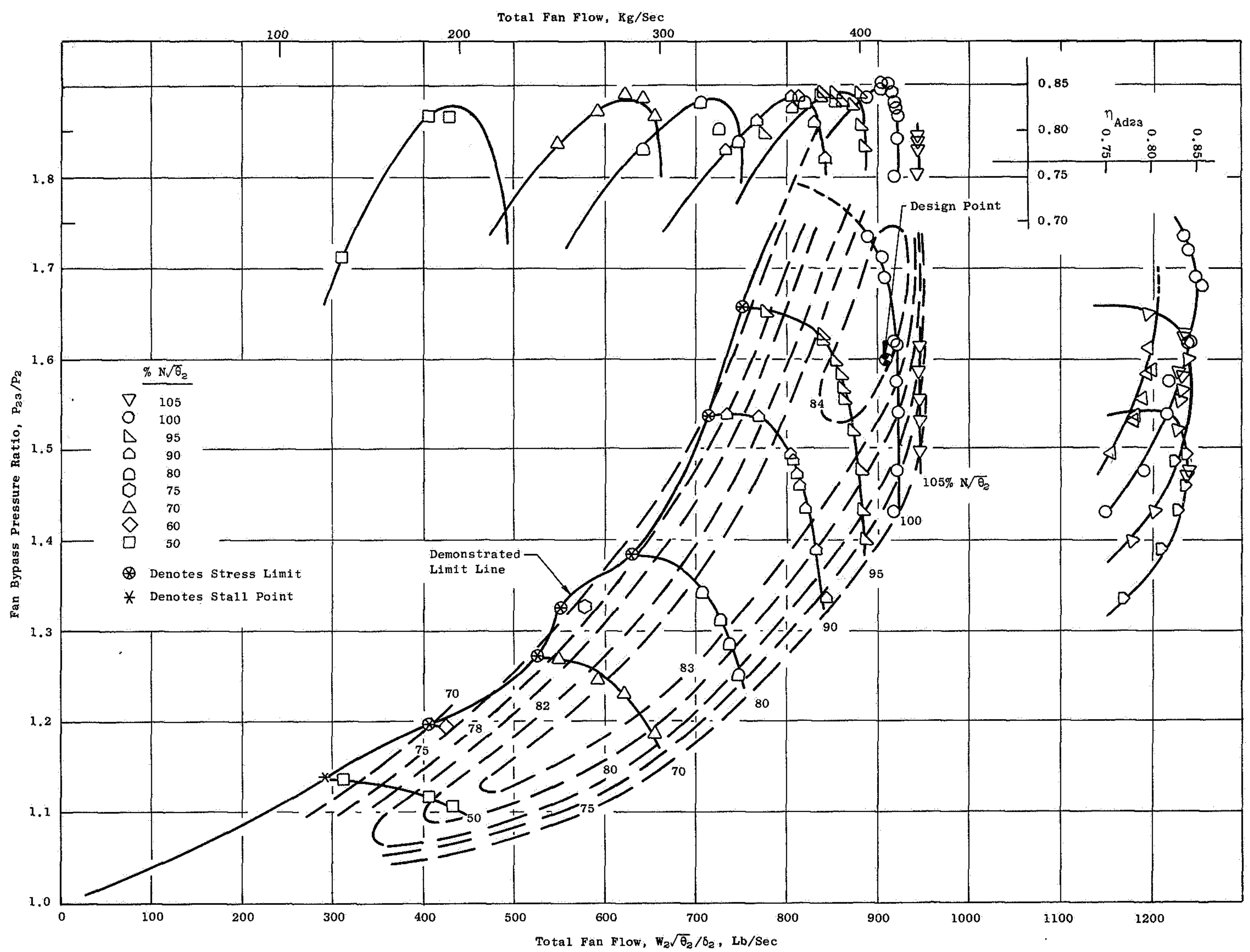

Figure 15. Fan A Performance Characteristics in the Bypass Region.

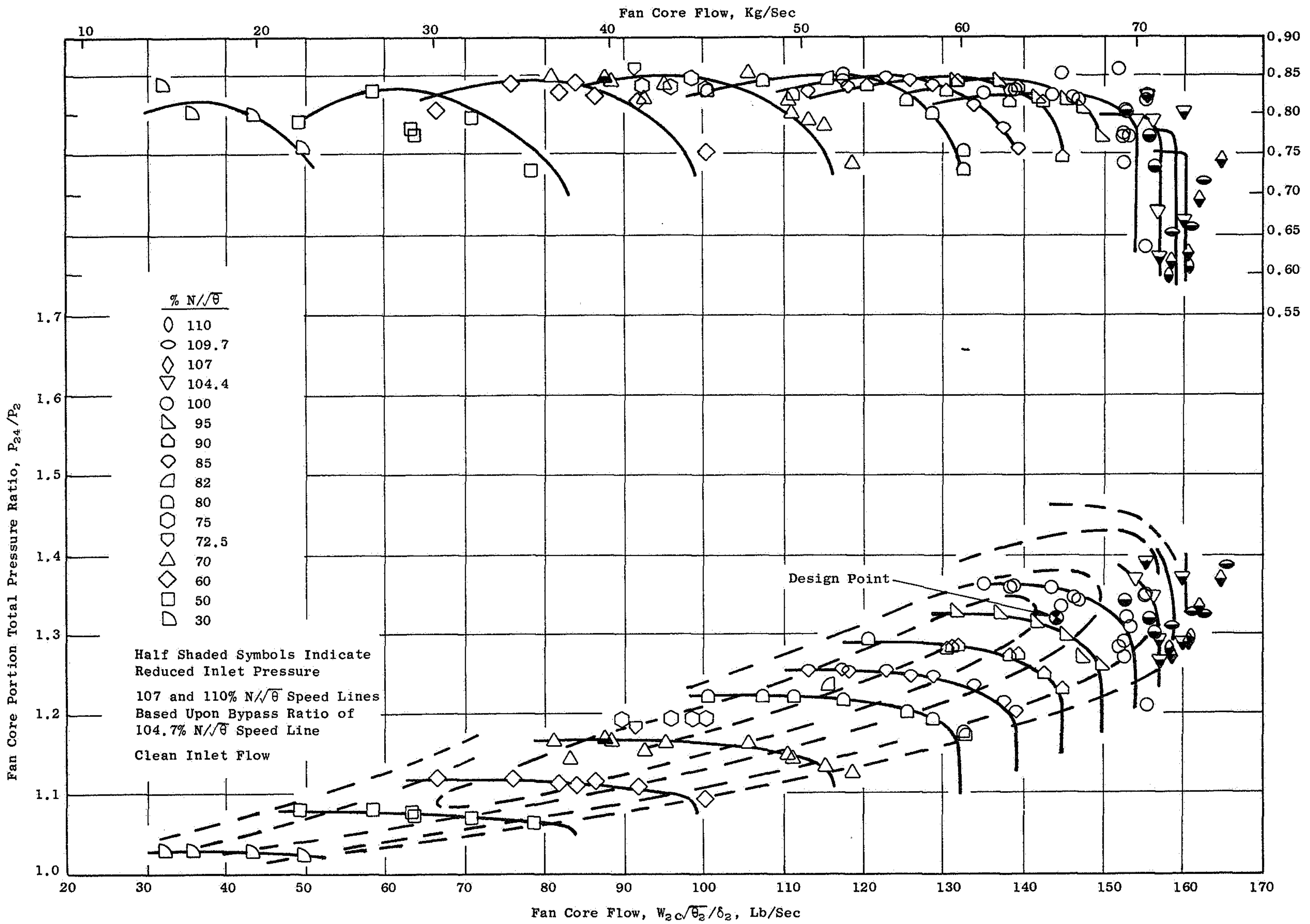

Figure 16. Fan A Performance Characteristics in the Core Region.

The fan was tested with one-per-rev circumferential, tip radial, and cross-wind distortion screens installed. Additional information on Fan A performance may be found in Reference 6.

(3) Performance of Fan B

The Fan B test vehicle was similar to that of Fan A. There were three configurations tested. The initial test (Build 1) had both vanes set at their design stagger angles. The rotor blades were initially made of aluminum.

Initial testing revealed that performance of the fan core outlet guide vanes was below expectations. The stagger angle of the aft element of the tandem row fan core OGV was increased 6° so as to unload the blade row, while the front element was left at the design stagger angle setting. The performance was improved somewhat by this modification. This configuration was referred to as Build 1A. During latter phases of testing, titanium rotor blades were substituted for the original aluminum blades to improve stress margins, and this configuration was referred to as Build 2. All test results presented in this report are for the Build 2 configuration, except as specifically noted.

Fan B was designed to deliver a bypass total-pressure ratio of 1.50 at a total fan flow of 950 lb/sec (430.9 kg/sec). The design bypass adiabatic efficiency was 87.0%. A bypass total-pressure ratio of 1.52 and an adiabatic efficiency of 86.9% at a flow of 966 lb/sec (438.2 kg/sec) were achieved in the test program. The peak adiabatic efficiency at design speed was 87.1% at a bypass pressure ratio of 1.507 and a total fan flow of 976 lb/sec (442.2 kg/sec). The fan core region was designed to develop a total-pressure ratio of 1.43 at a flow of 147.3 lb/sec (66.8 kg/sec). A fan core pressure ratio of 1.425 was achieved at its design flow and, at this condition, a fan core adiabatic efficiency of 77.0% was measured.

The operational limit lines were determined up to 100% corrected speed. Rotating stall was the operational limit at all speeds except 85% and 90% where high rotor stress precluded further increases in back pressure. At 100% corrected speed, an operating margin of 19.5% was achieved relative to the design operating line at altitude-cruise conditions; at 90% corrected speed the operating margin was 10.9% relative to the design operating line at sea-level-static conditions. The measured performance of Fan B is shown in Figures 17 and 18.

The fan was tested with one-per-rev circumferential, tip radial, and hub radial distortion screens installed. Additional information on Fan B performance may be found in Reference 7.

(4) Performance of Fan C

The Fan C test vehicle was similar to those of Fans A and C. Three configurations were tested. The initial test (Build 1) was as-designed, except that the stagger angle of the aft element of the tandem row fan core OGV was increased 4° (see Reference 8). The testing on Build 1 revealed that the

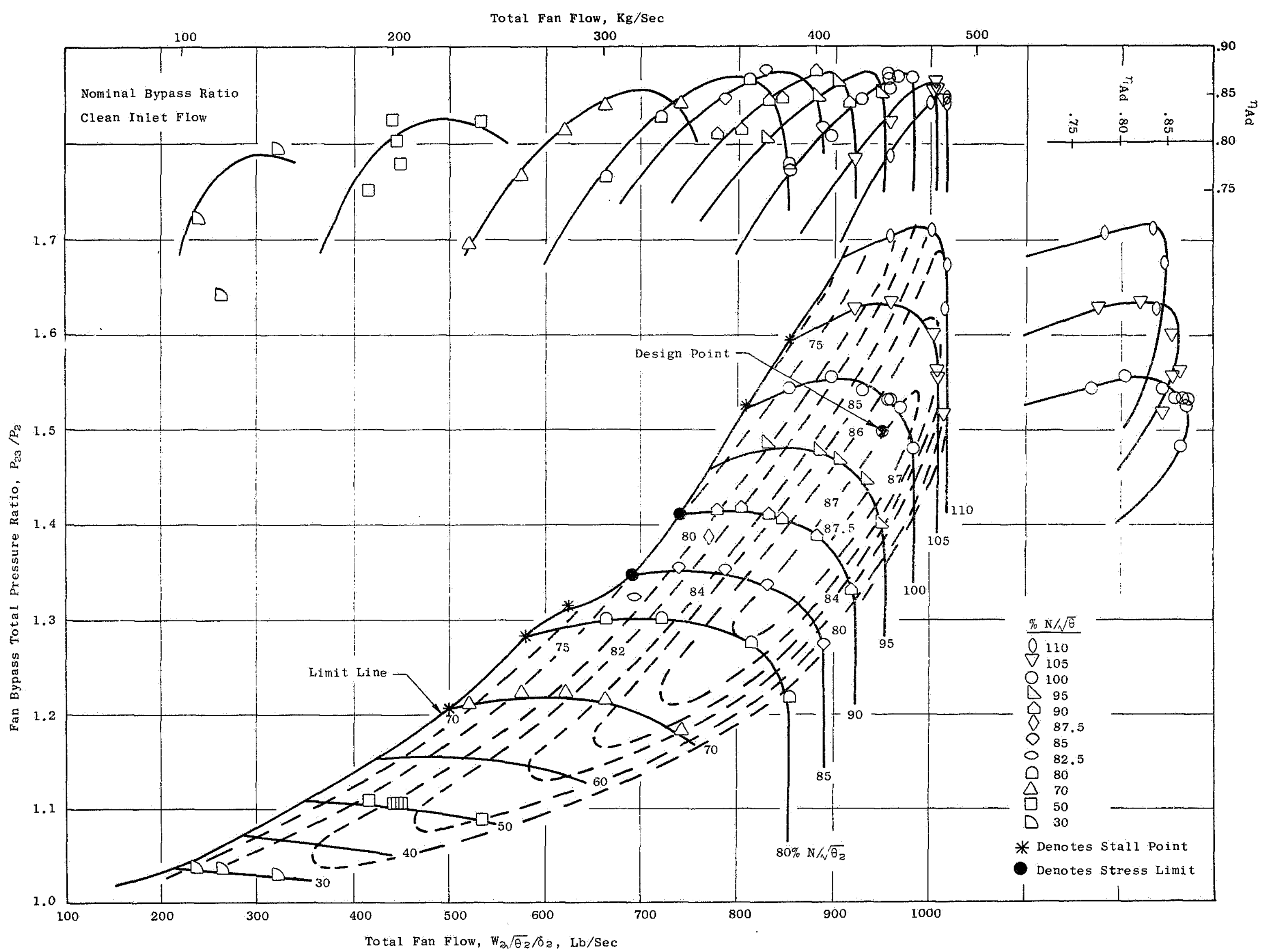

Figure 17. Fan B Performance Characteristics in the Bypass Region.

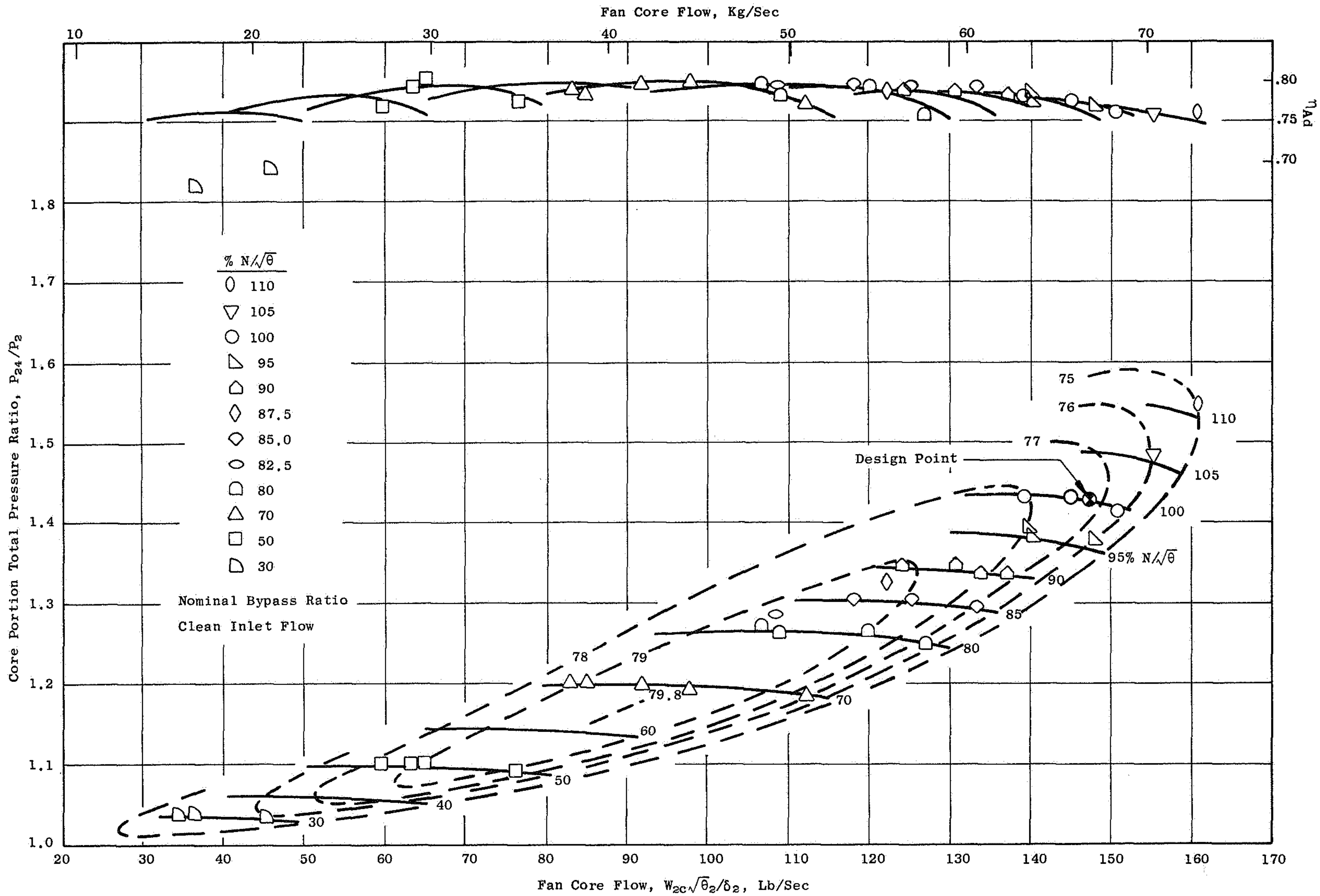

Figure 18. Fan B Performance Characteristics in the Core Region.

performance of the fan rotor was below expectations at corrected speeds below 104%. The test data indicated that the leading bow shock was not being "swallowed" at corrected speeds below 104%. To correct this deficiency, the rotor blades were modified (Build 2) to increase the external compression and to increase the throat area. Testing of Build 2 showed no performance gain relative to Build 1. Test data indicated that the leading bow shock was moved aft relative to Build 1, but was still not being "swallowed" in the manner expected. In a second attempt to correct this performance deficiency, the part-span shrouds were removed, and the blade was twisted closed by an amount slightly greater than the estimated additional mechanical untwist; this modification was designated Build 3. Objective performance was obtained with this configuration. All aerodynamic test results presented in this report are for the Build 3 configuration except as specifically noted. The Build 3 configuration is designated as "Mod II," which was incorporated in the Fan C half-scale model utilized in the acoustic development program.

Fan C was designed to deliver a bypass total-pressure ratio of 1.60 at a total fan flow of 915 lb/sec (415.0 kg/sec). The design bypass adiabatic efficiency was 84.2%. A bypass total-pressure ratio of 1.61 and an adiabatic efficiency of 83.9% at a flow of 921 lb/sec (417.8 kg/sec) were achieved in the test program. The peak design speed adiabatic efficiency was 85.0%, which occurred at a bypass pressure ratio of 1.68 and a total fan flow of 911 lb/sec (413.2 kg/sec). The fan core region was designed to develop a total-pressure ratio of 1.49 at a flow of 152.8 lb/sec (69.3 kg/sec). A fan core pressure ratio of 1.54 was achieved at its design flow; at this condition, a fan core adiabatic efficiency of 82.3% was measured.

The operational limit line was determined up to 95% corrected speed. Rotating stall was the operational limit at 50% corrected speed. At all corrected speeds from 60% to 95%, high rotor stress was the limit that precluded further increases in back pressure. The facility power limit was reached at 100% corrected speed prior to reaching the operational limit line. At this speed, the facility power limit point corresponded to an operating margin of 14.6% relative to the design operating line at altitude-cruise conditions. At 90% corrected speed, the operating margin was 17.4% relative to the design operating line at sea-level-static conditions. The measured performance of Fan C is shown in Figures 19 and 20.

The fan was tested with one-per-rev circumferential, tip radial, and crosswind distortion screens installed. Additional information on Fan C performance may be found in Reference 8.

b. Acoustic Evaluation

(1) Test Setup and Procedure

The General Electric acoustic test and evaluation program of scale model fans and full-scale engines was complemented by the NASA acoustic program of full-scale fans at the Lewis Research Center. Acoustic data were taken on configurations embodying Fans A, B, and C in the Lewis full-scale fan noise test facility. (see Figure 21).

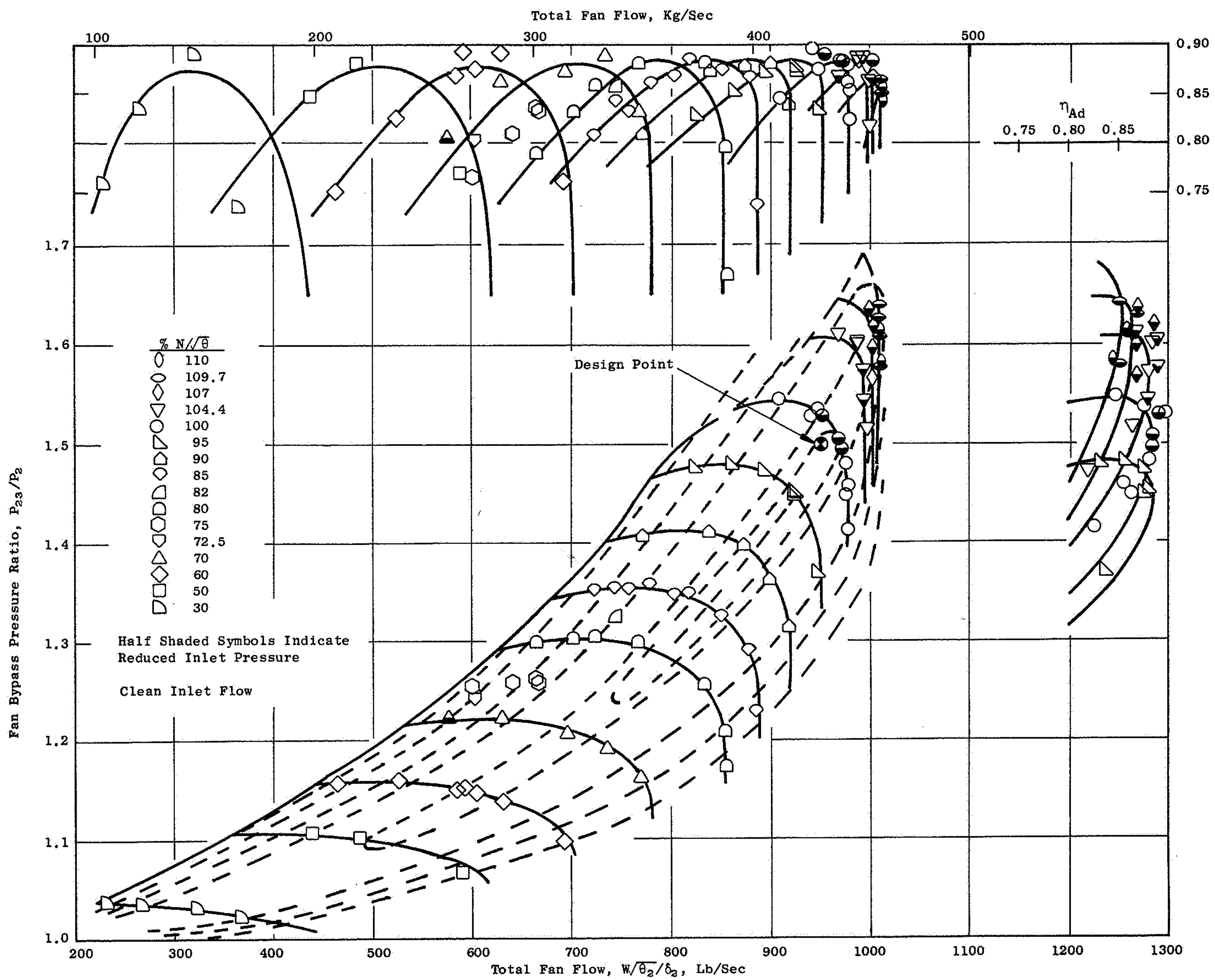

Figure 19. Fan C Performance Characteristics in the Bypass Region.

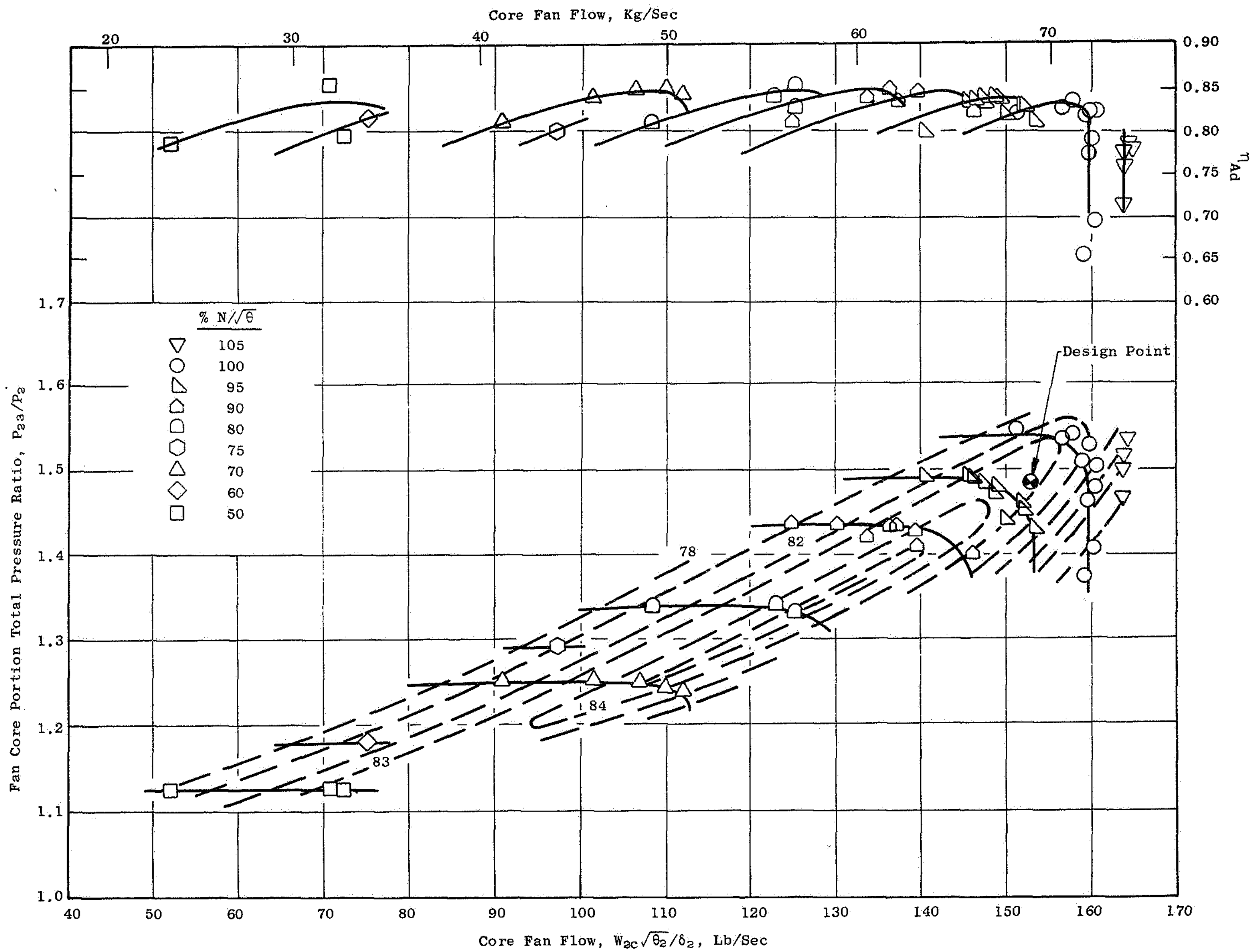

Figure 20. Fan C Performance Characteristics in the Core Region.

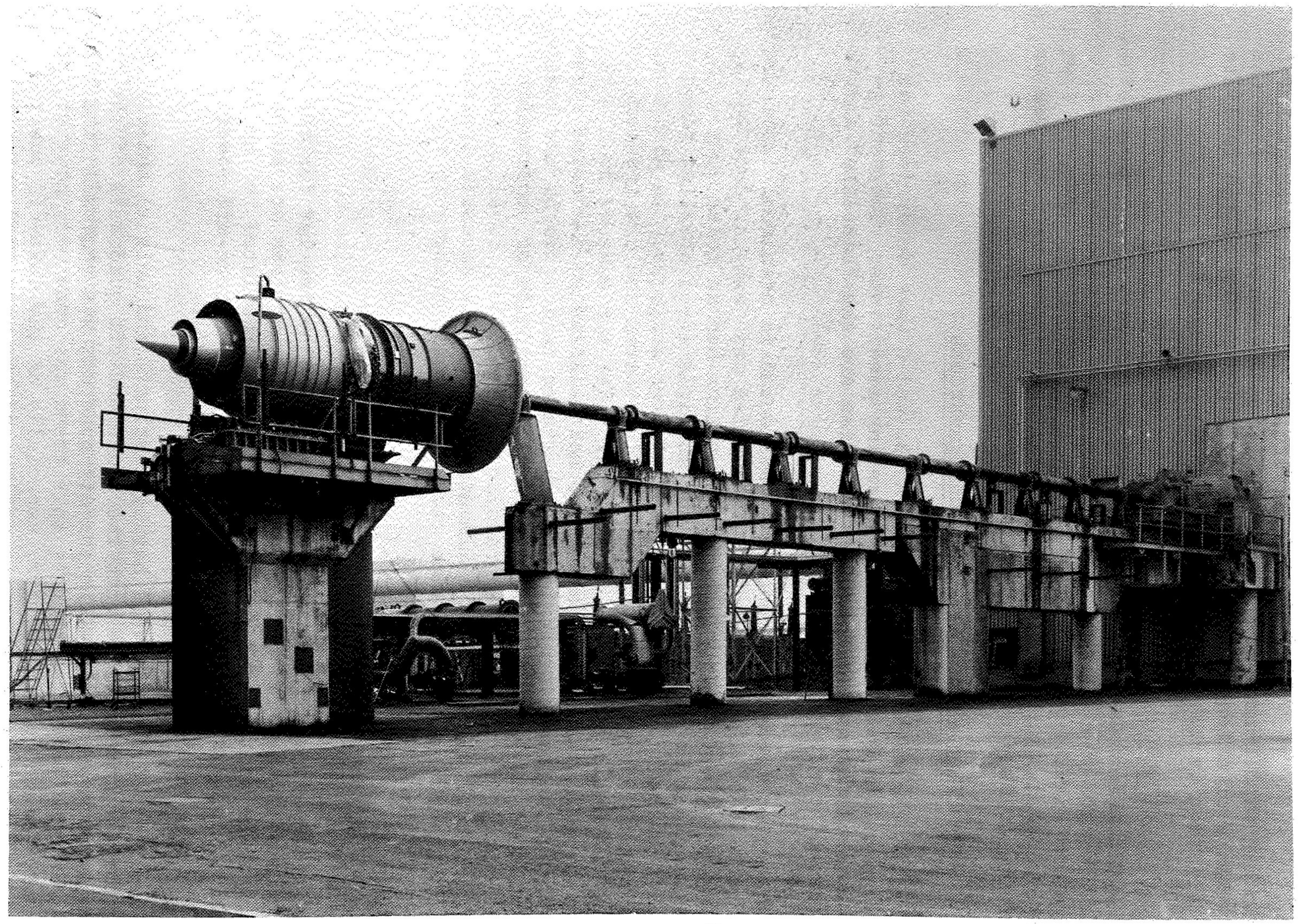

Figure 21. NASA-Lewis Full-Scale Fan Noise Test Facility.

Drive motors for the 10 × 10-foot (3.05 × 3.05-m) supersonic wind tunnel were utilized to power the fans. The fans were mounted on a pedestal 100 feet (30.5 m) from the wind tunnel drive motor building and were driven from the front-end by means of a long shaft. Additional information on the facility and the installation is contained in References 9, 10 and 11.

Noise measurements were made with 16 microphones located on a 100-foot (30.5-m) arc. The microphones were positioned at 10° increments from 10° to 160° as measured from the fan inlet centerline. The microphones were set above the asphalt sound field surface at the same height as the fan axis, 19 feet (5.8 m). Environmental restrictions (wind, humidity, etc.) were imposed on acoustic testing to assure reliable data.

(2) Full-Scale Fan Test Configurations

The acoustic characteristics of Fans A, B, and C were determined for various configurations over a range of operating conditions. Two configurations of major interest and common to each fan are the "baseline" and "fully suppressed" configurations.

The baseline configuration contained wall acoustic treatment incorporated in the fan frame (see Figure 22). All other inlet and exhaust duct walls were untreated. The fully suppressed configuration had an inlet duct suppressor with acoustic wall treatment and multiple (0-3) splitter rings with acoustic treatment on inner and outer splitter surfaces. In addition, the bypass exhaust duct walls were acoustically treated and one treated splitter ring was employed. While neither the inlet nor exhaust duct suppressors were aerodynamically optimized, nor tailored to the noise signature of the fans, the results obtained are believed indicative of the feasibility of fan noise suppression and the order of magnitude of suppression that may be expected in tailored suppression systems. Both baseline and suppressed configurations utilized bellmouth inlets. The acoustic treatment design for all three fans was the same except for small changes in treatment length.

(3) Full-Scale Fan Acoustic Test Results

The front and aft quadrant maximum perceived noise levels* for the Fans A, B, and C frame-treated and fully suppressed configurations are summarized in Table IV. These static test results have been extrapolated to the 200-foot (61-m) sideline, and are presented for the approach and take-off power settings.

Maximum perceived noise levels having distinct (and unique) noise characteristics were observed in both the front and aft quadrants of the fan configurations tested. The level in the aft quadrant was generally the higher of the two. An important exception to this trend was observed, however, for the Fan C frame-treated configuration, especially at the take-off power setting. Multiple pure tones strongly influenced the perceived noise levels of this high-tip-speed fan at the take-off setting.

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* See Reference 12.

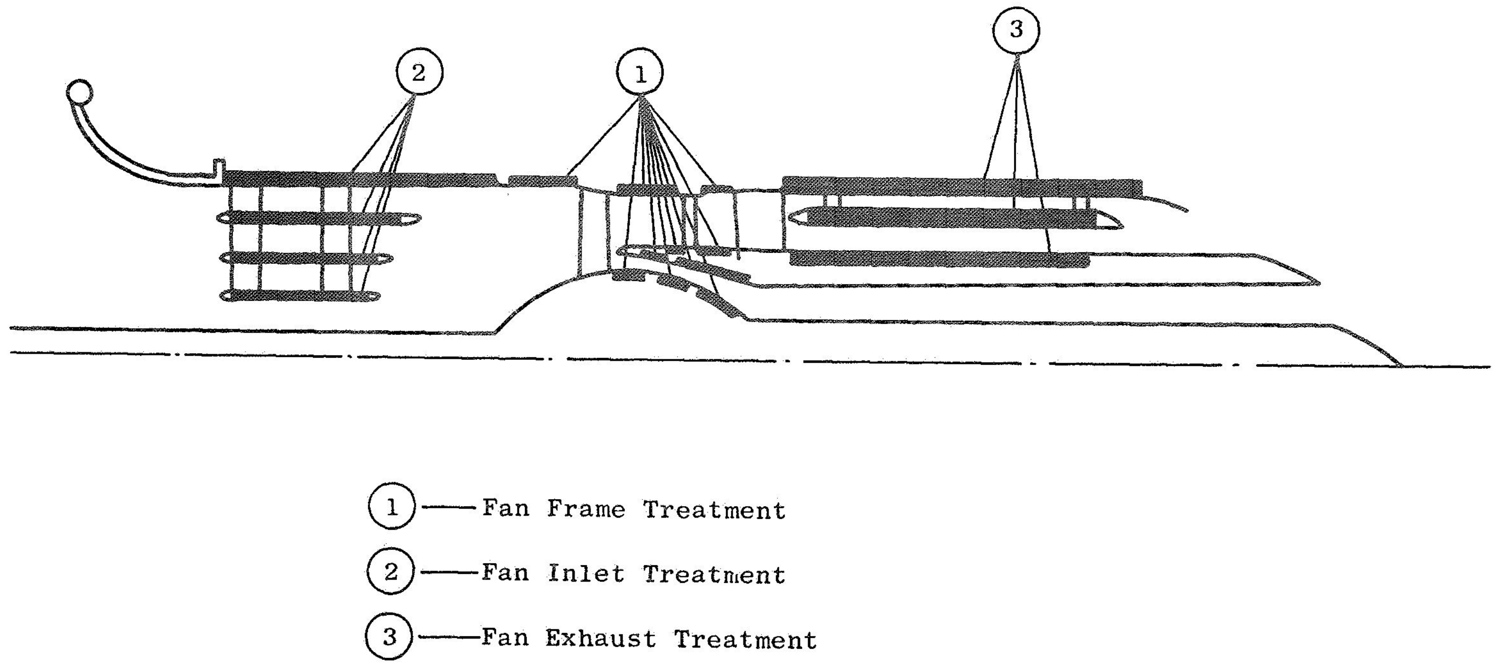


Figure 22. Component Fans A, B, and C, Fully Suppressed Configurations.

The same inlet and exhaust treatment was applied to each of the three fans. Comparisons indicated 9.0 to 12.0 PNdB suppression of the maximum front quadrant PNL's for Fans A, B, and C, as well as 4.6 to 8.3 PNdB suppression of the maximum aft quadrant levels. The installation of the inlet and exhaust treatment generally reduced the baseline perceived noise levels along the sideline more for Fan A than either Fans B or C, especially at the approach power setting.

Table IV. Full-Scale Fans Tested at NASA-Lewis Research Center, Summary of 200-foot (61-m) Sideline Front and Aft Maximum PNL.

Configuration	Front Quadrant		Aft Quadrant		Treatment Coded To Figure 22
	App	T/O	App	T/O	
Fan A					
Frame-Treated	105.2	115.0	104.9	117.5	1
Fully Suppressed	93.9	103.6*	96.7	110.6	1,2,3
Fan B					
Frame-Treated	102.8	114.4	107.0	118.9	1
Fully Suppressed	93.7*	102.7*	99.1	111.7	1,2,3
Fan C					
Frame-Treated	106.0	121.7	105.0	117.3	1
Fully Suppressed	96.6	111.1	99.6	112.7	1,2,3

*PNL's steadily decreased from a maximum in the aft quadrant. The 50° level was representative of the front quadrant noise.

Comparisons of the maximum perceived noise of the two lower-tip-speed frame-treated fans indicate that the Fan A levels were higher than those of Fan B in the front quadrant while being lower in the aft quadrant. The maximum PNL's for the fully suppressed configuration were similar for Fans A and B in the front quadrant, while the Fan A levels were again lower in the aft quadrant. The maximum levels for Fan C were higher than either Fans A or B in the front quadrant, especially at the take-off power setting. The maximum aft quadrant levels for Fan C were similar to those of Fan A in the frame-treated configuration and, likewise, similar to those of Fan B in the fully suppressed configuration.

In addition to general substantiation of the General Electric design and test results, the NASA program contributed directly to the integrated overall Experimental Quiet Engine Program. Acoustic comparisons between Fans A and B were utilized in the selection of Engine A as the lower-fan-tip-speed engine to be tested. Early information on the acoustic characteristics of Fan C was utilized to design acoustic treatment for the engine testing. Further, acoustic characteristics of Fans A and C were compared to corresponding engine test results in order to evaluate the contribution of the fan component to the overall engine noise levels.

The full-scale fan acoustic data discussed above are taken from References 10 and 11 for Fans B and A, respectively. The Fan C data are based on unpublished NASA results. Reference 9 gives additional information on the test program.

2. Half-Scale Fan Test Facility and Procedures

Testing of the scale model fan vehicles was performed at the Peebles Test Operation, General Electric's outdoor test site, using a General Electric LM1500 stationary gas turbine as the drive system through the fan inlet. This test facility permits scale model fan measurements of acoustic and aerodynamic performance characteristics. Both Fan B (0.484 scale factor) and Fan C (0.527 scale factor) were tested in many configurations in the 36-inch (91.4-cm) diameter vehicle, simulating the bypass flow portion of the full-scale fans. In the pretest engine and component design phase of the program, Engine B was predicted to have the lowest noise levels of the three engines (see Reference 1). Further, Fans B and C had the same numbers of blades and vanes, while Fan A had different numbers. Therefore, the half-scale program was based on Fans B and C, as examples of low- and high-tip-speed engines.

The acoustic data were taken with microphones located on a 100-foot (30.5-m) arc, positioned at 10° increments from 30° to 160° as measured from the fan inlet axis. The microphones were set at the height of the fan centerline, 12 feet (3.66m) above the sound field surface of, initially, crushed stone. Later testing was over asphalt, with microphones at a height of 15 feet (4.57m) and with calibrations to assess the different acoustic properties of the two ground surfaces. In the case of Fan B, the "baseline", tip bleed and serrated rotor tests were conducted with crushed stone, while the variable pitch and leaned outlet guide vane tests were conducted with asphalt. All fan C tests were conducted with asphalt. (See Reference 13).

Restrictions were imposed on acoustic testing to assure reliable data. Thus, appropriate "windows" for maximum allowable winds and range of relative humidity were established. No testing was conducted with water or snow accumulation on the sound field, or with rain, snow, or fog conditions. Aerodynamic instrumentation was removed.

3. Half-Scale Fan B Testing

a. Test Configurations

The design of Fan B is discussed in Section III of this report, as well as in Reference 1. Five separate sets of investigations were conducted on Half-Scale Fan B, as described in the following sections. The testing comprised

6 configurations of the "baseline" fan (untreated and with frame treatment*), 5 configurations for casing tip bleed investigations, 6 configurations for serrated rotor evaluation, 60 different variable pitch configurations, and 6 configurations for evaluation of the effect of outlet guide vane lean.

b. Half-Scale Fan B Baseline

The baseline configuration of Half-Scale Fan B was tested with three different exhaust nozzles - nominal, 16% oversized, and 6% undersized. Figure 23 shows a cross section of the model fan in the treated configuration. The untreated configuration was obtained by neutralizing the treatment by covering with adhesive-backed foil tape. Table V shows 200-foot (61-m) sideline maximum PNL's (Reference 12) for all configurations at approach and take-off power settings. The noise levels shown are scaled to full-scale Fan B size. The fan exhaust nozzle area changes did not reduce noise at take-off and approach thrust levels, although the large nozzle (16% oversized) did show the lowest noise in the mid-thrust range. Fan frame acoustic treatment was effective in reducing maximum 200-foot (61-m) sideline PNL by 4.2 PNdB at take-off and approach power settings, the suppression obtained being over a frequency range of 1 - 10 kHz. Pretest flyover noise predictions agreed quite well with test results for unsuppressed noise. Further detailed information on the baseline fan acoustic and aerodynamic investigations is given in Reference 14.

c. Half-Scale Fan B Casing Tip Bleed

Half-Scale Fan B was tested with a rotor tip casing bleed slot, using the treated baseline configuration discussed in Section b above. The slot was continuous circumferentially, flush with the original casing contour, and located 1/2 inch (1.27 cm) upstream of the leading edge of the rotor tip. Testing was done at 0, 2, 3, and 4% bleed flow (percent of total fan flow) at both approach and take-off power settings, and results were compared with those of the standard casing configuration. Table V shows acoustic results of the investigations. Although increasing bleed flow decreased both broadband and tone noise compared to the zero bleed case using the slotted casing, the standard (unslotted) configuration had lower noise than any bleed configuration. The noise in the front quadrant decreased relative to the zero bleed baseline with increasing bleed rate. This type of bleed might reduce noise if the inlet boundary layer were highly turbulent or if blow-in doors were used. Further detailed information on the casing tip bleed acoustic and aerodynamic investigations is given in Reference 15.

d. Half-Scale Fan B Serrated Rotor

Since the wakes shed from the rotor blades are among the principal mechanisms of noise generation, boundary layer control on the blades can reduce the effect of the wakes. One method for achieving this is to serrate the blade leading edges. Half-Scale Fan B was tested with serrated rotor blades, in the treated baseline configuration discussed in Section b above.

*The frame treatment was 1/2-inch (1.27-cm)-thick Scottfelt, covered by a perforated plate.

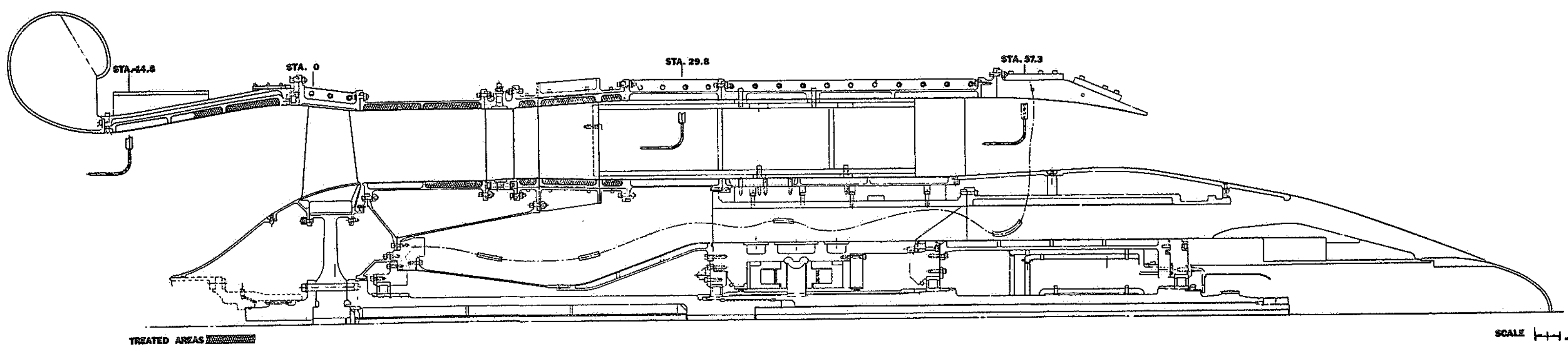


Figure 23. Fan B Scale Model Cross Section, Indicating Location of Acoustic Treatment.

Table V. Half-Scale Fan B Configurations, Summary of 200-foot (61-m) Sideline Front and Aft Maximum PNL (Scaled to Full-Scale Fan B Size).

Configuration	Exhaust Nozzle	Front Quadrant		Aft Quadrant		Remarks
		Approach	Takeoff	Approach	Takeoff	
Baseline, treated	Small	100.4	111.0	101.6	113.6	All entries in PNdB
Baseline, treated	Nominal	98.0	109.9	100.2	112.4	---
Baseline, treated	Large	98.8	110.4	100.8	113.6	---
Baseline, untreated	Small	102.6	110.9	106.8	117.5	---
Baseline, untreated	Nominal	101.0	109.9	104.4	116.6	---
Baseline, untreated	Large	101.1	110.3	106.0	117.2	---
Standard casing	Nominal	98.0	109.9	100.2	112.4	No bleed
Bleed casing	Nominal	102.5	112.5	104.1	115.6	No bleed
Bleed casing	Nominal	102.2	113.3	104.0	115.5	2% bleed
Bleed casing	Nominal	101.3	113.1	103.7	115.3	3% bleed
Bleed casing	Nominal	100.0	111.6	103.6	114.5	4% bleed
Normal rotor	Small	100.4	111.0	101.6	113.6	---
Serrated rotor	Small	100.1	110.7	103.8	115.6	---
Normal rotor	Nominal	98.0	109.9	100.2	112.4	---
Serrated rotor	Nominal	99.9	109.2	103.7	113.4	---
Normal rotor	Large	98.8	110.4	100.8	113.6	---
Serrated rotor	Large	97.8	108.5	102.7	113.5	---
Normal rotor	Small	105.0	---	108.2	---	---
Variable rotor	Small	101.8	113.7	105.7	118.2	Minimum noise stagger
Normal rotor	Nominal	102.8	111.6	106.5	116.7	---
Variable rotor	Nominal	100.7	111.2	104.7	116.5	Minimum noise stagger
Normal rotor	Large	101.4	112.7	106.0	117.8	---
Variable rotor	Large	100.0	112.5	105.3	117.3	Minimum noise stagger
Radial OGV	Small	103.0	115.3*	105.4	118.0*	---
Leaned OGV	Small	103.0	113.1	105.3	116.7	---
Radial OGV	Nominal	101.5	113.0	105.3	117.3	---
Leaned OGV	Nominal	100.5	112.3	103.0	115.0	---
Radial OGV	Large	99.9	111.0	103.0	116.8	---
Leaned OGV	Large	98.9	110.3	102.2	114.5	---

* Extrapolated entries.

Three exhaust nozzle configurations were again utilized. Table V shows acoustic results in terms of maximum PNL at the 200-foot (61-m) sideline, scaled to full-scale Fan B size. The serrations reduced front quadrant PNL's at take-off power. However, rear quadrant PNL's were increased by serrations at both approach and take-off power. The serrations reduced blade passing frequency SPL values significantly in the front quadrant at take-off thrust; with the nominal nozzle, the fundamental PWL was reduced 4.2 dB. The serrated rotor had negligible effect on the operating lines of the model fan. Further detailed information on the serrated rotor acoustic and aerodynamic investigations is given in Reference 16.

e. Half-Scale Fan B Variable Pitch

A variable pitch rotor version of Half-Scale Fan B was tested in the baseline configuration. Twenty different rotor blade stagger settings were used for each of the three exhaust nozzles. Table V shows maximum PNL values for the minimum noise stagger configurations for each exhaust nozzle at approach and take-off thrust settings. Approach thrust for the variable pitch Fan B was taken at 44% thrust, rather than 39% thrust as in the case of the other Fan B vehicles investigated, because of test facility limitations with the variable pitch vehicle. Evaluation of acoustic and fan efficiency data for the nominal exhaust nozzle case shows that the stagger angles for minimum noise tend to be the same as the maximum efficiency settings. The results of the variable pitch investigations indicate that a variable (or reverse pitch) fan can be scheduled so as to reduce noise and increase efficiency at off-design thrust levels. In general, the PNL reduction is obtained through broadband noise reduction. Blade passing frequency and harmonic noise tend to increase at constant thrust. Further information on the variable pitch fan acoustic and aerodynamic investigations is given in Reference 17.

f. Half-Scale Fan B Leaned OGV

The effect of radially leaning the outlet guide vanes by 30° in the direction of rotor rotation was evaluated. Tests were made with both leaned and nominal (radial) OGV's, with fan frame treatment, and three exhaust nozzles. Table V shows the 200-foot (61-m) sideline maximum PNL's, comparing leaned and radial vanes, indicating definite noise reductions due to lean at both approach and take-off power settings.

Regarding aerodynamic performance of the leaned and radial vane fans, it should be noted that little difference was caused by lean in corrected flow at pressure ratio at a given corrected speed. However, lean improved fan efficiency in this case. Additional information on the acoustic and aerodynamic investigations of Half-Scale Fan B with leaned outlet guide vanes is given in Reference 18.

g. Summary of Half-Scale Fan B Testing

The experimental investigations with Half-Scale Fan B had the following salient results:

- With the baseline configuration, the fan exhaust nozzle area changes did not reduce noise at take-off and approach thrust levels, although the large nozzle (16% oversized) did show the lowest noise in the mid-thrust range. Fan frame acoustic treatment was effective in reducing maximum 200-foot (61-m) sideline Perceived Noise Level (PNL) by 4.2 PNdB at both takeoff and approach power settings.

- The casing tip bleed investigations showed that the particular rotor tip casing bleed slot increased the noise level above that of the configuration without the bleed slot.

- The serrations reduced front quadrant PNL's at take-off power, but increased rear quadrant maximum PNL's at approach thrust. The serrations reduced blade passing frequency SPL values significantly in the front quadrant at take-off thrust; with the nominal nozzle, the fundamental power level (PWL) was reduced 4.2 dB.

- The variable pitch rotor investigations showed that a variable (or reverse pitch) fan can be scheduled so as to reduce noise and increase efficiency at off-design thrust levels.

- Investigations with leaned outlet guide vanes showed that circumferentially leaned outlet guide vanes can be used to reduce the noise of low-tip-speed fans.

4. Half-Scale Fan C Testing

a. Test Configurations

The detailed design of Fan C is discussed in Section III of this report, as well as in Reference 1. Five separate sets of investigations were conducted on Half-Scale Fan C. The testing comprised four configurations of wall acoustic treatment, two configurations for investigation of rotor casing slots, four configurations of rotor blade/flow passage shape modifications both with and without acoustic treatment, nine configurations of inlet noise control via wall/splitter acoustic treatment and inlet duct Mach number control, and six configurations for evaluation of the effect of outlet guide vane lean.

b. Half-Scale Fan C Nacelle Treatment

Half-Scale Fan C was tested with four configurations of wall acoustic treatment, as follows:

- No acoustic treatment

- Fan frame treatment

- Full nacelle wall treatment

- Full nacelle wall treatment with a massive aft suppressor

Figure 24 shows the location of the acoustic treatment [Scottfelt, 1/2-inch (1.27-cm) thick] for the frame and nacelle treatment cases, as well as the "massive aft suppression." For untreated testing, the massive aft suppressor was removed and the treated areas neutralized by covering them with adhesive-backed foil tape. Table VI shows 200-foot (61-m) sideline maximum PNL's for take-off and approach power settings. Full nacelle treatment reduced front maximum noise by 8.3 PNdB at take-off power and 7.2 PNdB at approach power. The inlet suppression was more effective on takeoff than on approach, while the aft duct suppression was more effective on approach than on takeoff. The massive aft suppression isolated the inlet-radiated noise, and the results showed that the noise in the front quadrant was totally inlet-radiated even without the suppressor. Additional information on the acoustic and aerodynamic investigations of Half-Scale Fan C with various treatment configurations is given in Reference 13.

c. Half-Scale Fan C Slotted Tip Casing

Half-Scale Fan C was tested with a circumferentially slotted-tip casing in order to determine the acoustic effect of slots designed to improve fan stall margin. Acoustic treatment was also placed behind the slots to assess the possibility of additional noise suppression. The slotted configurations included fan frame treatment as defined in Section b above. Table VI shows acoustic results of the slotted-tip casing tests. The slots increased the aft quadrant noise over the frame treatment/solid casing levels, particularly at approach. The addition of treatment behind the slots reduced noise levels slightly. Comparison of the solid and slotted casing results on the fan aerodynamic performance map shows little change. However, there are indications of efficiency improvement due to slot addition, particularly at 90% corrected speed. Further information on the slotted-tip casing acoustic and aerodynamic investigations with Half-Scale Fan C are given in Reference 13.

d. Half-Scale Fan C Blade Modifications

Four damperless configurations of Half-Scale Fan C were tested in an effort to reduce multiple pure tone (MPT) noise. Each configuration was tested with and without wall acoustic treatment. For the untreated configurations, the treatment was neutralized by covering it with an adhesive-backed foil tape. Figure 25 shows an overlay of the four rotor blade tip airfoil shapes. In each case tested, the basic intent was to alter the shock structure so as to reduce the multiple pure tone (MPT) noise. The airfoil labeled "Mod II" was designed by "conventional" practices. That is, the design point (100% corrected fan speed) performance was a key criterion. Since performance of high speed blading is highly dependent on the bow shock position, the airfoil shape and cascade gemoetry are tailored to put the shock in a "swallowed" position which results in a minimum of shock losses. One of the acoustic characteristics of such a blade is a drop-off in noise level as thrust is increased past the take-off thrust. With this in mind, it was reasoned that, if the design shock position was obtained at takeoff, the take-off noise would be lower. The "Mod III" blade represents this design. From the performance point of view, this design change was expected to decrease design point efficiency. The next blade shape selected ("Mod VII") was actually obtained from "Mod III" by

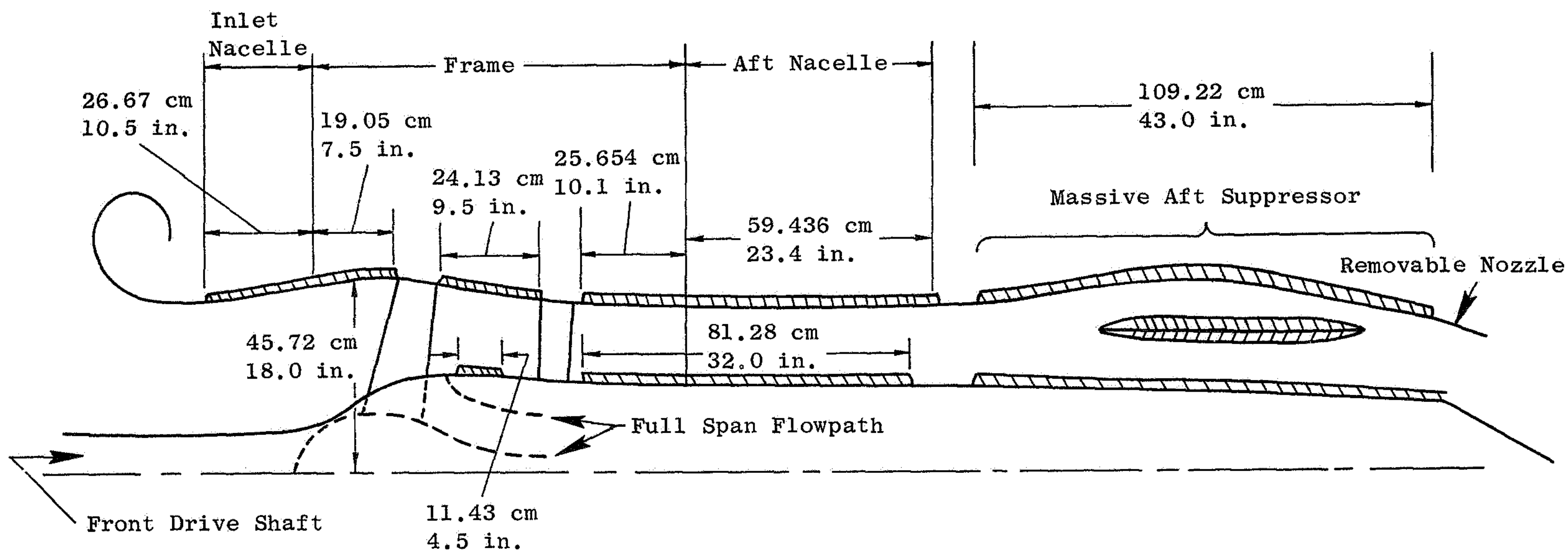


Figure 24. Fan C Scale Model Treatment Lengths.

Table VI. Half-Scale Fan C Configurations, Summary of 200-foot (61-m) Sideline Front and Aft Maximum PNL (Scaled to Full-Scale Fan C Size).

Configuration	Exhaust Nozzle	Front Quadrant		Aft Quadrant		Remarks
		Approach	Takeoff	Approach	Takeoff	
Untreated	Nominal	105.3	123.1	105.8	119.7	All entries in PNdB
Frame treatment	Nominal	102.6	120.4	102.0	117.2	---
Full nacelle treatment	Nominal	98.1	114.8	96.2	112.0	---
Massive aft suppression	Nominal	99.0	114.9	94.5	110.5	---
Unslotted tip, frame treatment	Nominal	102.6	120.4	102.0	117.2	---
Slotted tip, untreated*	Nominal	101.4	120.0	104.2	118.0	---
Slotted tip, treated*	Nominal	100.5	119.8	103.7	117.3	---
Blade Mod II, untreated	Nominal	105.2	123.0	105.4	119.6	See Table VII for additional results of the blade modification investigations.
Blade Mod II, treated	Nominal	97.5	104.5	96.0	110.8	---
Blade Mod III, untreated	Nominal	104.2	120.3	106.8	119.1	---
Blade Mod III, treated	Nominal	98.5	105.2	96.5	110.7	---
Blade Mod VII, untreated	Nominal	102.7	120.6	107.1	119.6	---
Blade Mod VII, treated	Nominal	95.5	106.5	97.2	112.3	---
Blade Mod VIII, untreated	Nominal	107.5	122.5	107.6	119.8	---
Blade Mod VIII, treated	Nominal	103.2	107.0	100.4	113.2	---
Inlet suppression	---	---	---	---	---	See Table IX for results of the inlet suppression investigations
Radial OGV	Small	100.0	116.4	102.9	116.5	---
Leaned OGV	Small	100.3	116.0	104.1	117.0	---
Radial OGV	Nominal	99.0	114.0	101.0	116.0	---
Leaned OGV	Nominal	99.5	117.0	104.5	118.0	---
Radial OGV	Large	98.0	117.0**	102.0	116.5**	---
Leaned OGV	Large	100.0	119.0**	103.3	118.0**	---

* Slotted configurations include frame treatment. "Slotted tip, treated" implies treatment behind the slots.

** Entries are extrapolated.

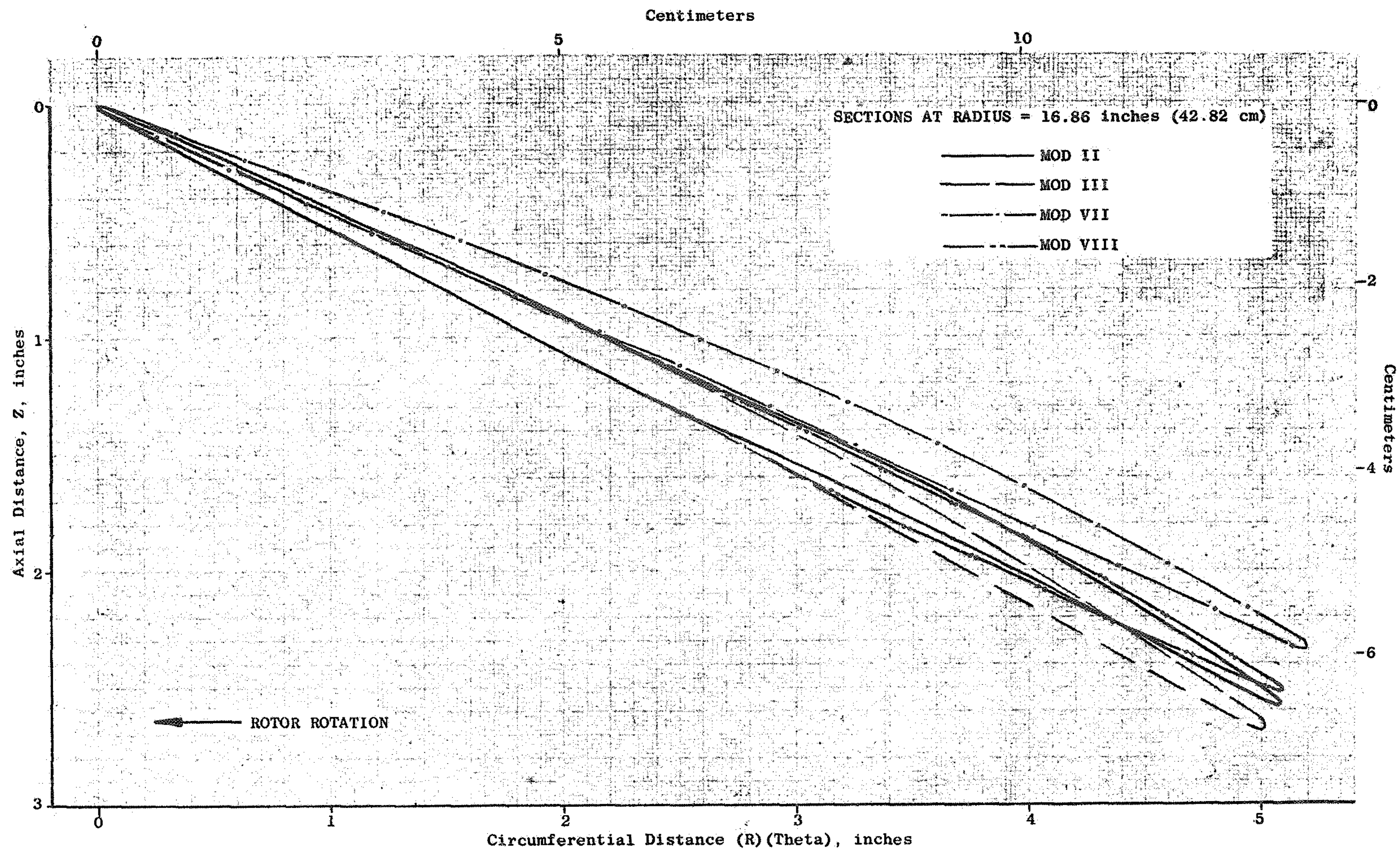


Figure 25. Fan C Scale Model Modifications for Blade Tip Contour.

closing the blade. It was hypothesized that this would help to increase the design point performance without affecting the noise output. One of the side effects of this change was that at a given corrected speed the flow and pressure ratio were lower than they were for "Mods II and III." The last blade selected for testing, designated "Mod VIII," was an attempt to bring about an increase in design point efficiency while maintaining the acoustic characteristics of the "Mod III" blade design. The "Mod VIII" blade was thickened at the tip in order to change the aerodynamic characteristics by weakening the secondary shock in the cascade. Also, in order to maintain the same general performance characteristics, it was necessary to decrease the tip slope.

During evaluation of the 1/3-octave band sound pressure levels for the take-off power setting at the 200-foot (61-m) sideline for the dominant multiple pure tones, the blade passing frequency tone, and the second harmonic tone, it was found that the rotor blade modifications decreased the multiple pure tone levels as desired, but increased the blade passing frequency and second harmonic tone levels. Table VI shows the maximum PNL's at the 200-foot (61-m) sideline. Table VII summarizes the front maximum level-flyover PNL's for the treated and untreated configurations at approach and takeoff. It will be noted that in flight the untreated "Mod VIII" blade was 2.8 PNdB quieter than "Mod II" at takeoff.

Table VII. Half-Scale Fan C Blade Modifications - Level Flyovers - Scaled Maximum Forward PNL (With Predicted Core Jet).

Mod	Approach (370 ft, 112.8 m)		Takeoff (1000 ft, 304.8 m)	
	Untreated	Treated	Untreated	Treated
II	99.4	91.8	107.5	97.8
III	98.9	93.2	103.8	99.2
VII	97.6	90.6	103.7	99.2
VIII	101.3	97	104.7	99.6

For each of the blade configurations, the performance map was determined by using a set of fixed nozzles with various areas. Table VIII shows aerodynamic performance of each configuration at 60 and 95% corrected speed, using the nominal 396 in^2 (0.255 m^2) nozzle. The results show that at low speed "Mod VIII" passed less flow than "Mod II", while at higher speed, "Mod VIII" passed more flow. "Mod VIII" had a smaller annulus area and, therefore, passed less actual flow at the design speed. However, the specific flow (lb/ft^2) (kg/m^2) of the two fans was comparable. At low speed "Mod VIII" efficiency was approximately equal to that of "Mod II". At high speed, "Mod VIII" was about 2% higher in efficiency than "Mod II". It must be noted that the relatively short span of these blades resulted in a somewhat lower absolute efficiency level than a lower-radius-ratio fan. This is due to the high Mach number over the hub wall which locally reduces efficiency. However, on a

Table VIII. Half-Scale Fan C Blade Modifications - Aerodynamic Performance.

Mod	60% $N/\sqrt{\theta_2}$			95% $N/\sqrt{\theta_2}$		
	Pressure Ratio	$W\sqrt{\theta_2}/\delta_2$ lb/sec (kg/sec)	η_{Ad}	Pressure Ratio	$W\sqrt{\theta_2}/\delta_2$ lb/sec (kg/sec)	η_{Ad}
II	1.182	109.7 (49.8)	0.804	1.562	180.0 (81.6)	0.812
III	1.189	111.8 (50.7)	0.827	1.548	178.2 (80.8)	0.796
VII	1.182	109.7 (49.8)	0.860	1.506	172.0 (78.0)	0.788
VIII	1.171	107.0 (48.5)*	0.805	1.575	181.4 (82.3)	0.832

*NOTE: Mod VIII from scaled to Mod II by the ratio of rotor inlet areas.

comparative basis, these results are significant. Additional information on the Half-Scale Fan C blade modification investigations is given in Reference 19.

e. Half-Scale Fan C Inlet Suppression

The Half-Scale Fan C model was tested to determine the effects on noise of varying the number of treated inlet splitters, and inlet Mach number effects. Each test was run with wall acoustic treatment. A total of eight suppressed configurations was run. Since these investigations evaluated front end noise, the "massive aft suppressor" was used in all cases to remove rear-radiated fan noise from the front quadrant. Figures 26 through 28 show the various inlets tested. Table IX shows a summary of the forward maximum PNL, throat Mach number and total-pressure recovery at take-off and approach fan speeds. It can be seen in Table IX that the three-splitter inlet with acceleration from Mach 0.46 (untreated baseline) to 0.67 reduced the noise 17.2 PNdB at takeoff with an inlet recovery loss of 2.9%. At approach, acceleration was from 0.26 to 0.35 with a noise reduction of 12.8 PNdB and a recovery loss of 0.7%. With one splitter the 0.79 inlet showed a reduction of 18.1 PNdB at takeoff with an acceleration of 0.46 to 0.72 and a recovery loss of 2.3%. When no splitters were employed, the reduction at takeoff in going from the unsuppressed to the 0.55 inlet was 11.0 PNdB. With acceleration from 0.54 to 0.71 (see note §§ in Table IX), a further reduction of 3.9 PNdB was realized. The total noise reduction, 14.9 PNdB, was obtained at a cost of 1.3% in recovery. Noticeable noise reductions due to acceleration were found at Mach numbers of 0.65 and higher.

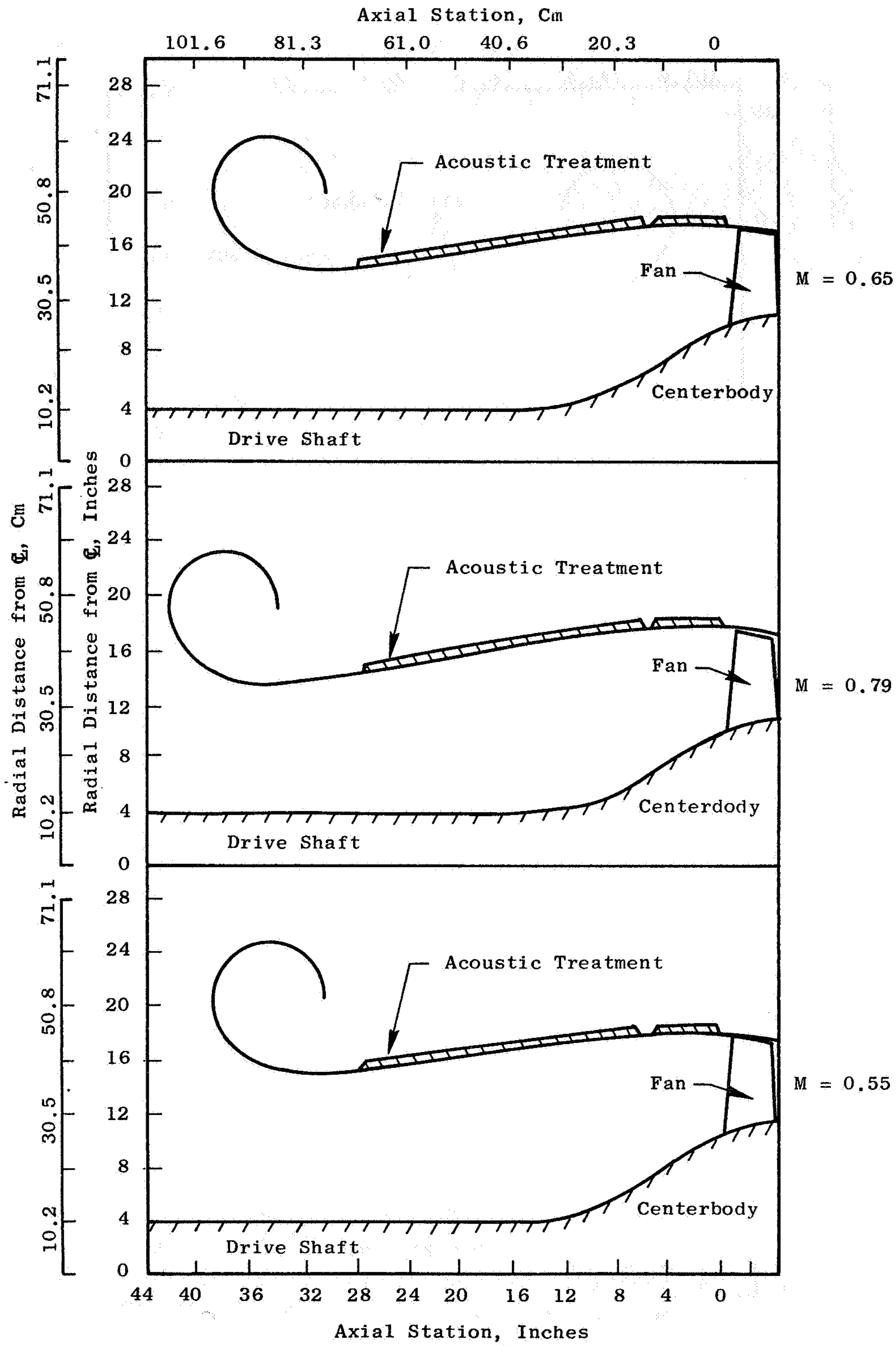


Figure 26. Fan C Scale Model Inlets without Splitters.

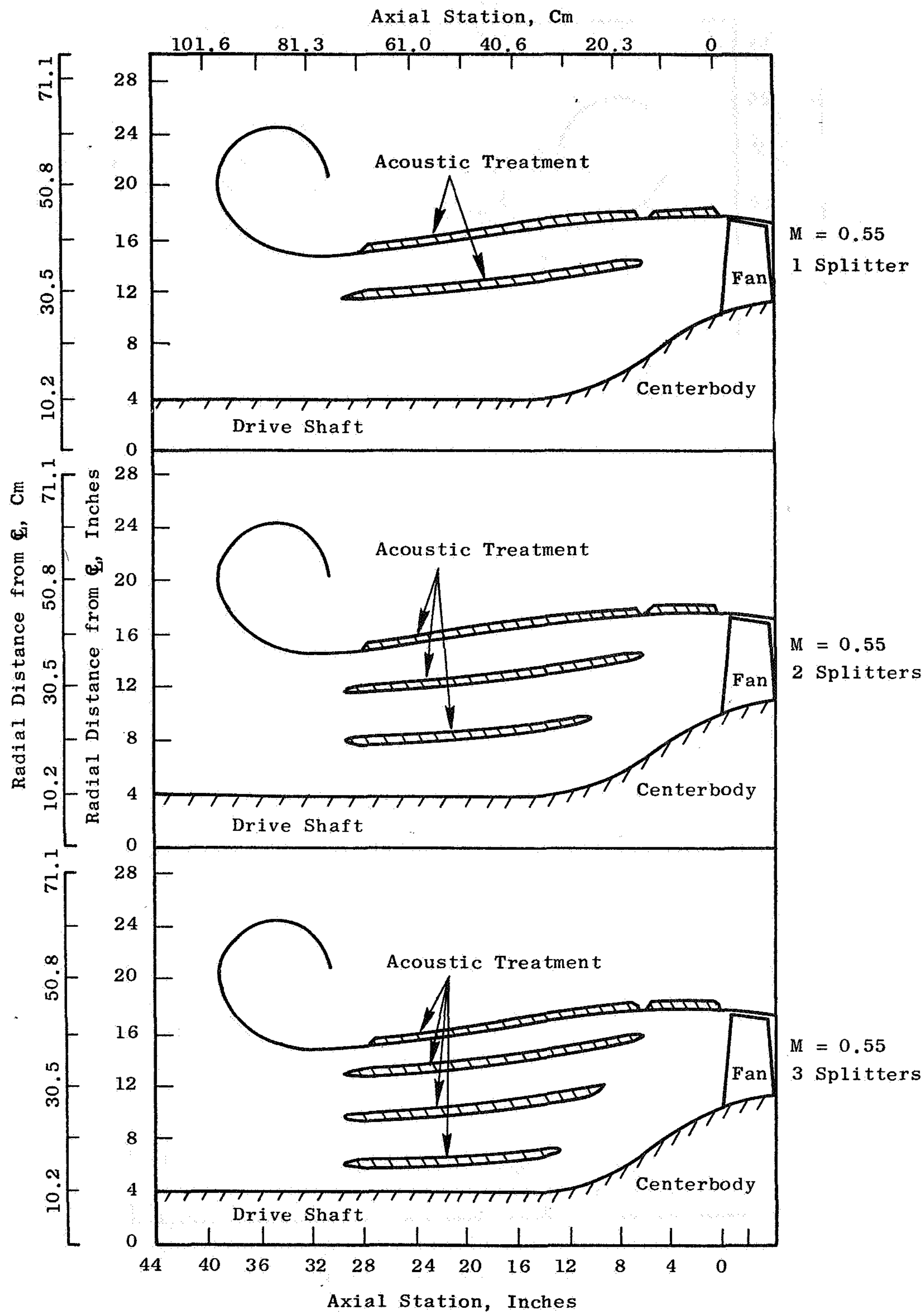


Figure 27. Fan C Scale Model Inlets with Varying Splitters.

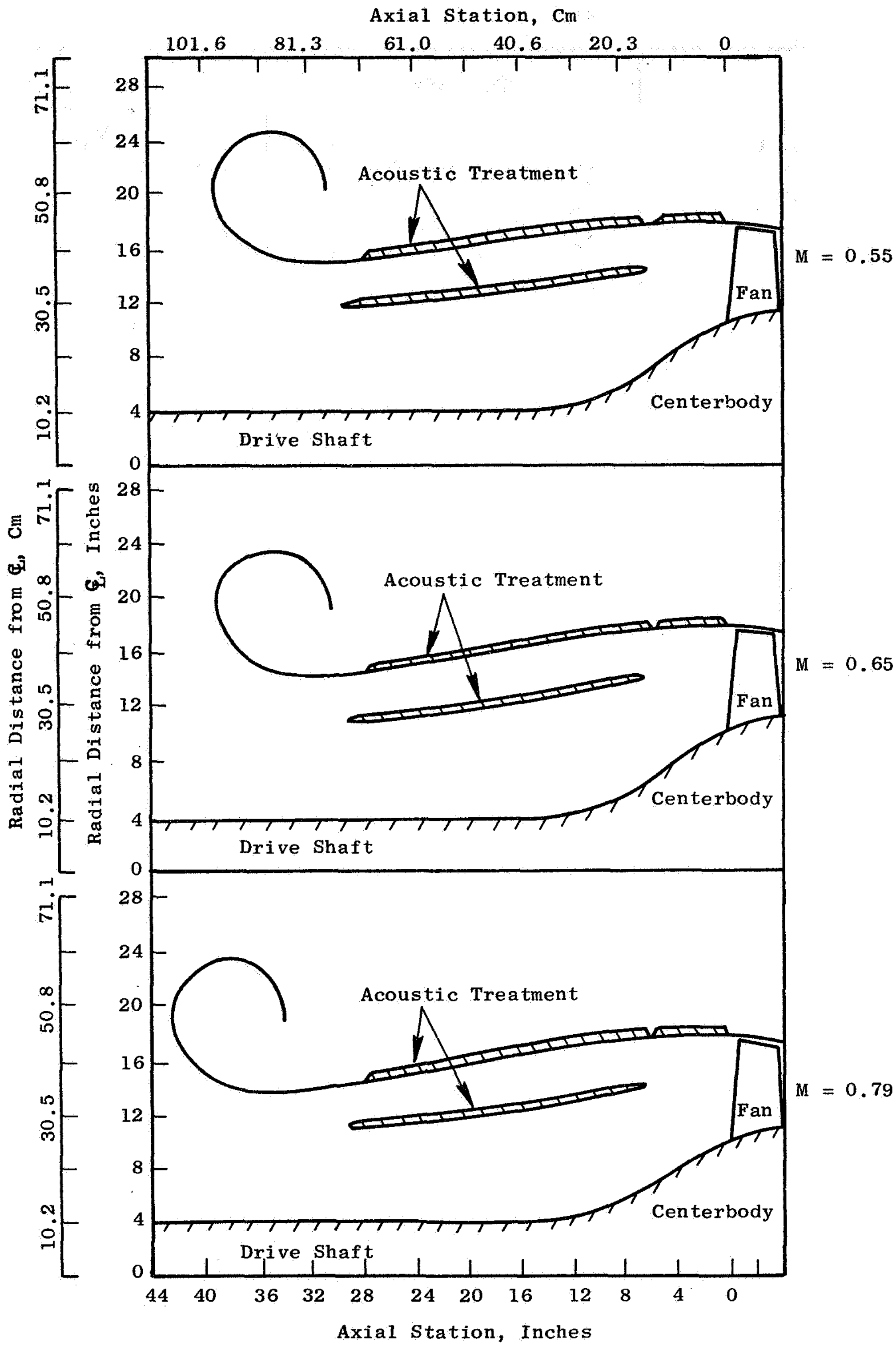


Figure 28. Fan C Scale Model Inlets with One Splitter.

Table IX. Half-Scale Fan C Inlet Suppression Investigation - Inlet Noise†, Mach Number‡, and Recovery§ Summary.

Configuration	Takeoff††			Approach‡‡		
	PNL	M_{TH}	η_r	PNL	M_{TH}	η_r
Unsuppressed	122.9	0.46	0.997	105.1	0.26	0.998
0.55 No splitter	111.9	0.54	0.994	98.5	0.30	0.998
0.55 One splitter	110.2	0.57	0.982	95.0	0.31	0.991
0.55 Two splitters	108.6	0.61	0.982	94.7	0.33	0.996
0.55 Three splitters	105.7	0.67	0.968	92.3	0.35	0.991
0.65 No splitter	112.9	0.62	0.992	99.4	0.33	0.997
0.65 One splitter	109.3	0.68	0.977	96.8	0.35	0.992
0.79 No splitter§§	108.0	0.71	0.984	99.8	0.37	0.996
0.79 One splitter	104.8	0.72	0.974	96.7	0.37	0.995

† 200-ft (61-m) sideline maximum forward angle full-scale PNL.

‡ Average throat Mach number based on flow and total-pressure recovery.

§ Average total-pressure recovery.

†† Takeoff is defined as 90% corrected fan speed.

‡‡ Approach is defined as 57.5% corrected fan speed.

§§ Takeoff data at 88% corrected fan speed.

It should be noted that the splitters were added such that the inlet throat was smaller in each case. At higher speeds the Mach number was considerably higher than the conventional inlet (usually 0.5 to 0.55). The inclusion of splitters resulted in noise reduction at the cost of inlet recovery. With no splitters the inlet behaved in the normal manner with recovery at 0.994 at 90% speed. As splitters were added, recovery dropped with the lowest value being 0.962 (Mach number was about 0.7) measured with three splitters. The single-splitter inlet showed lower recovery than the two-splitter inlet except at high speed. It is believed that this loss in recovery was the result of a misalignment of the single splitter with respect to the flow. The effect of this on the noise reduction obtained is unknown, although it did not appear to have caused any discontinuities in the acoustic data.

Roughly, a 1% decrease in recovery resulted in a 2% thrust loss on the Engine C cycle. Therefore, recovery levels will have to be carefully considered in engine suppression design. Additional information on the acoustic and aerodynamic inlet noise reduction investigations with Half-Scale Fan C are given in Reference 20.

f. Half-Scale Fan C Leaned OGV

The effect of radially leaning the outlet guide vanes by 30° in the direction of rotor rotation was tested. Tests were made with both leaned and normal (radial) OGV's, with inlet and fan frame treatment. Three exhaust nozzles were used. Table VI shows the 200-foot (61-m) sideline maximum PNL's, comparing leaned and radial vanes, indicating noise increases accompanying lean on Fan C. The noise increase is largely associated with increased high frequency broadband noise. However, there are indications that the noise increase is not generally applicable to all high speed fans. This belief is based on the detection of an apparent OGV incidence mismatch in Fan C which may have affected the noise generation. In regard to aerodynamic performance of the leaned- and radial-vane fans, the leaned-vane fan showed a trend toward higher flow at a given corrected speed. There is no apparent reason for this behavior. There was some loss in fan efficiency with lean with the nominal exhaust nozzle. When the small and large nozzles were used, the leaned vanes produced higher efficiencies at several speed points. Additional information on the acoustic and aerodynamic investigations of Half-Scale Fan C with leaned outlet guide vanes is given in Reference 18.

g. Summary of Half-Scale Fan C Testing

The experimental investigations with Half-Scale Fan C gave the following salient results:

- The nacelle treatment investigations showed that with full nacelle treatment, the inlet suppression was more effective at takeoff than at approach, and the aft duct treatment was more effective at approach than at takeoff.

- Investigations with the slotted-tip casing showed that the grooves above the rotor increased the aft-radiated noise, particularly at low power settings. Including a single-degree-of-freedom acoustic treatment behind the grooves reduced front noise levels. The grooved fan casing appeared to improve the fan efficiency about one percent at corrected speeds near design.

- The rotor blade modification investigations showed that a change in the basic blade airfoil design criteria can act to reduce multiple pure tone (MPT) noise in fans with supersonic relative Mach numbers. Future design changes aimed at reducing multiple pure tones must acknowledge the possibility that the blade passing frequency noise will increase, which was the result in these investigations.

- Investigations with the inlet suppression configurations showed that multiple acoustically treated splitters and/or a high average throat Mach number resulted in appreciable take-off noise reduction.

- The leaned outlet guide vane investigations with Fan C showed that radially leaned outlet guide vanes increased noise level. However, there are indications that this is not a result which is generally applicable to all high speed fans.

B. Engine Aero/Acoustic Testing

1. Test Facility and Procedures

Testing of Engines A and C was performed at the Peebles Test Operation, General Electric's outdoor test site. This test facility permits full-scale engine measurements of acoustic and aerodynamic performance characteristics. Figure 29 shows an aerial view of the engine test sound field.

Acoustic data were recorded using 16 calibrated microphones located on a 150-foot (45.7-m) arc. The microphones were positioned at 10-degree intervals from 10° to 160° as measured from the engine centerline at the axial position of the rotor leading edge. These microphones were attached to towers at a height of 40 feet (12.2 m) above the level sound field surface covered with gravel, in order to simulate ground reflections typical of fly-over conditions. In that the engine centerline height was 13 feet (4.0 m), the actual distance from the center of the sound field at the fan rotor to each individual microphone was about 152.5 feet (46.5 m).

For Engine A, noise levels were measured for 11 configurations. In all, 107 hours of acoustic and aerodynamic testing were completed at the Peebles site with Engine A. Farfield acoustic data for each configuration were recorded at seven speed points (plus repeat runs for validation).

For Engine C, noise levels were measured for 13 engine configurations. In all, 144 hours of acoustic and aerodynamic testing were completed at the Peebles site with Engine C. Farfield acoustic data were recorded for each configuration at six speed points (with repeats).

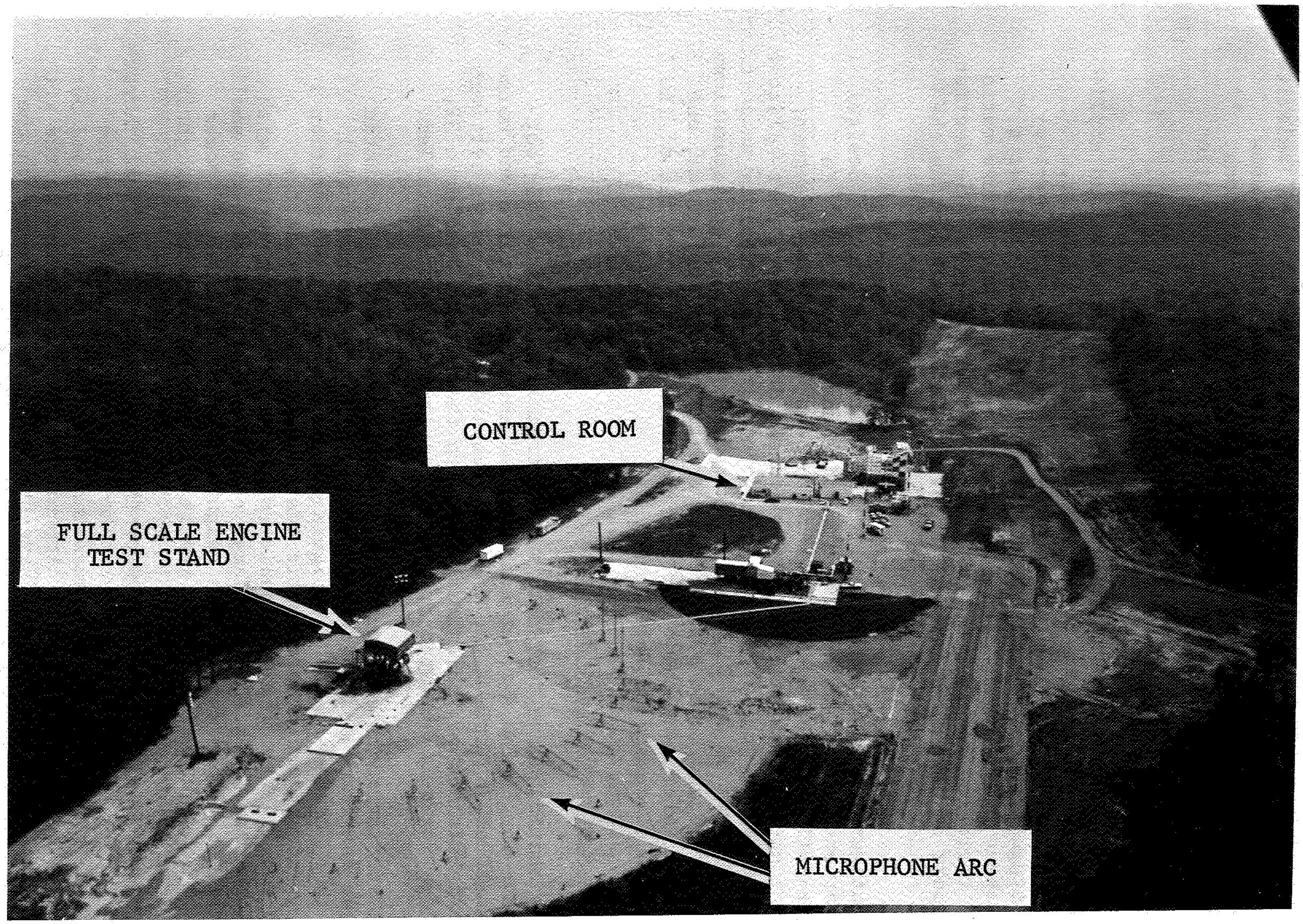


Figure 29. Aerial View of GE-Peebles Sound Field.

Restrictions were imposed on acoustic testing to assure reliable data. Thus, appropriate "windows" for maximum allowable winds and range of relative humidity were established. No testing was conducted with water or snow accumulation on the sound field, or with rain, snow, or fog conditions. Aerodynamic instrumentation was removed during acoustic data acquisition.

2. Engine A Test Configurations

In order to investigate low-fan-speed engine characteristics and applicable noise reduction techniques, Engine A was constructed. This 22,000 pound (97,900N) thrust class turbofan engine was based on a new, low-tip-speed, single-stage fan, designed at the altitude cruise condition for a corrected tip speed of 1160 ft/sec (353.6 m/sec), at a bypass pressure ratio of 1.5, with a corrected fan flow of 950 lbs/sec (430.9 kg/sec). See Section III of this report as well as Reference 21 for complete information on the engine.

Eleven configurations were examined to determine the effect of design/treatment variations on the engine system's noise characteristics. In particular, the following features were investigated: fan frame treatment, (baseline), core engine exhaust treatment, engine inlet designs, duct splitter treatment, engine casing wrapping, and engine operating line (various exhaust nozzle sizes). Figures 30 and 31 show two examples of Engine A configurations mounted on the test stand, both being "Frame Treatment" configurations, one having a bellmouth inlet, and the other a "thick-lip" inlet. Details of the configurations are discussed in Reference 21.

3. Engine A Acoustic Test Results

All of the static engine test data were extrapolated to the 200-foot (61-m) sideline. The Engine A front and aft quadrant maximum perceived noise levels are summarized in Table X for the approach and take-off power settings. The engine configurations of Table X are coded to those shown in Figure 32, where the various Engine A acoustic treatment configurations are detailed.

The "baseline" Engine A configuration investigated contained acoustic treatment in the fan frame and compressor inlet only. The acoustic wall treatment for this "frame-treated" configuration is shown as Configuration 1 on Figure 32. Evaluation of the acoustic test results showed that the maximum PNL at the 200-foot (61-m) sideline produced at a given thrust with this configuration was lowest for the large nozzle and highest with the small nozzle. The highest levels were in the neighborhood of the take-off power setting, above which the maximum PNL's remained steady or decreased slightly.

The fan fundamental and harmonics were the most prominent spectral characteristics of this fan (especially at the take-off power setting). It was observed for the "frame-treated" configuration that the fundamental stood out in the front quadrant while the second harmonic was very prominent in the aft quadrant. Although operation of the "frame-treated" configuration with the large nozzle did produce the lowest noise levels of the three operating lines examined, the pretest SFC requirements for cruise could not be met with the

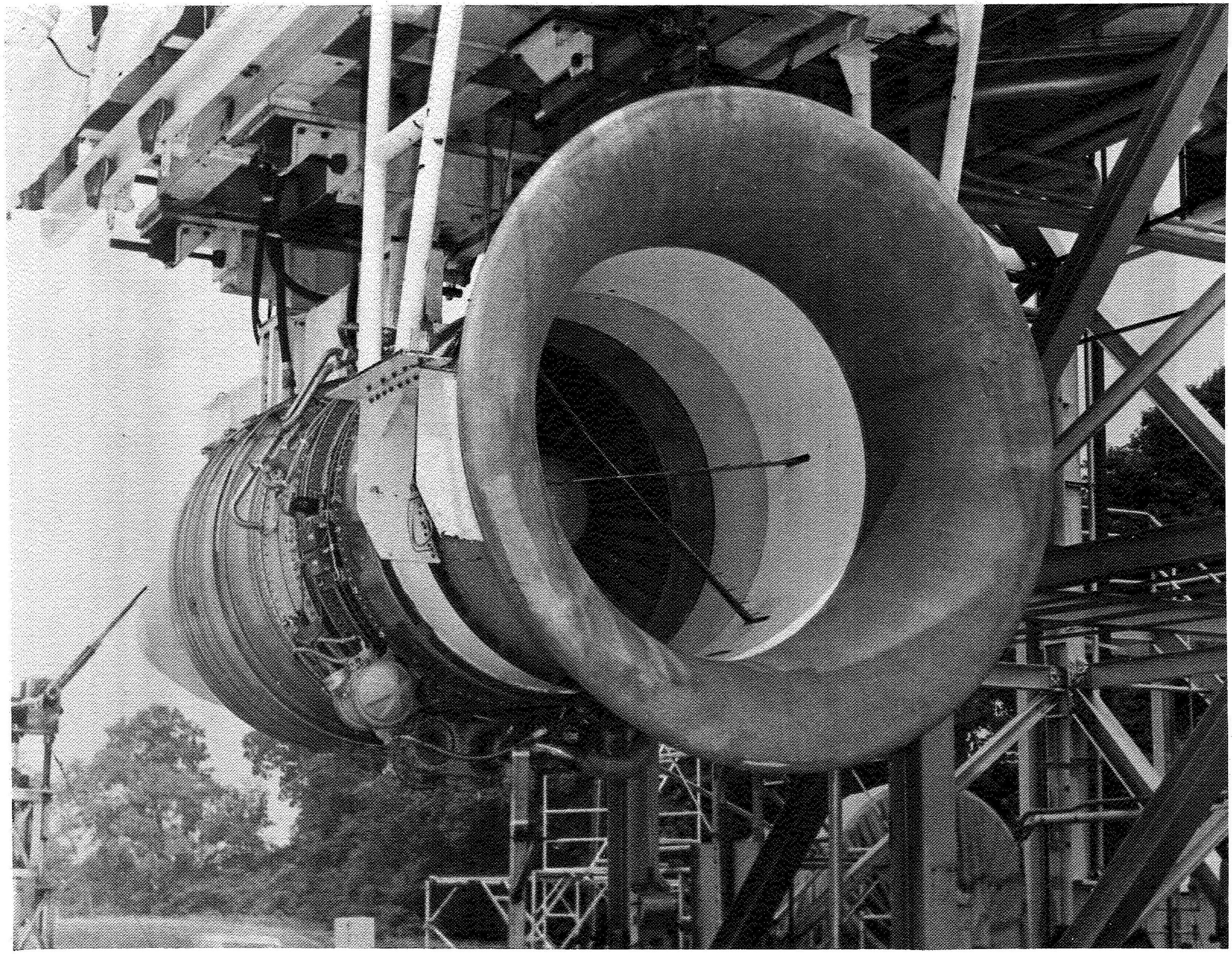


Figure 30. Quiet Engine **A** with Bellmouth Inlet, on Test Stand.

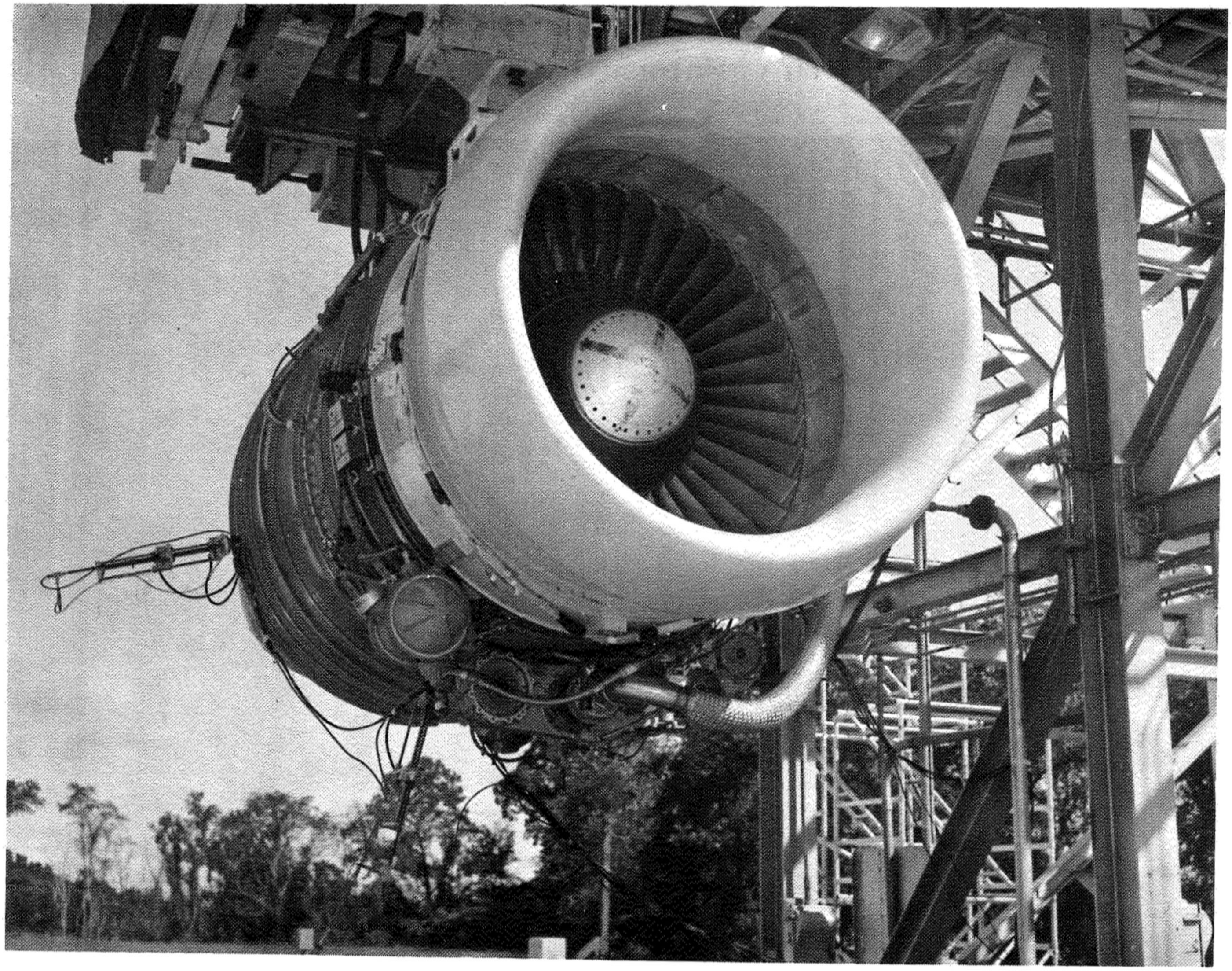
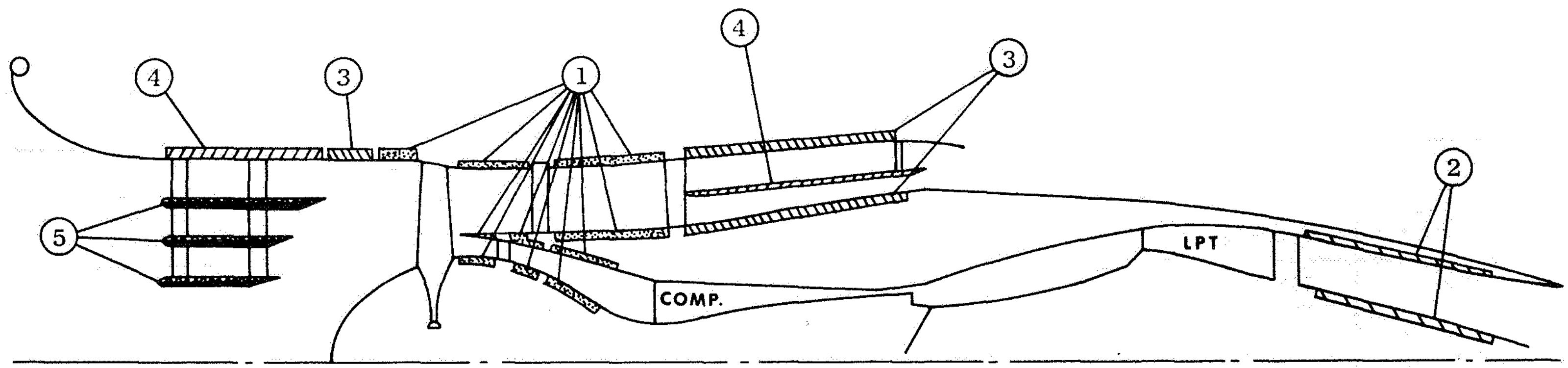


Figure 31. Quiet Engine A with Thick-Lip Inlet, on Test Stand.

Table X. Engine A Configurations, Summary of 200-foot (61-m) Sideline Front and Aft Maximum PNL.

Configuration	Nozzle Size	Approach				Takeoff				Treatment Coded to Figure 32
		Front		Aft		Front		Aft		
		PNL	Angle	PNL	Angle	PNL	Angle	PNL	Angle	
Fan frame treatment (Baseline)	Nominal	104.3	50°	105.5	110°	113.5	60°	117.9	120°	1
Fan frame treatment	Small	104.8	50°	105.3	120°	113.6	60°	119.1	120°	1
Fan frame treatment	Large	102.1	50°	103.6	120°	113.7	60°	117.1	120°	1
Treated core nozzle (fan frame treatment only)	Nominal	103.8	50°	104.5	120°	113.7	60°	117.2	120°	1,2
Thick-lip inlet	Large	102.7	60°-80°	105.0	120°	112.5	70°	117.4	130°	1,2
Blow-in-door inlet	Large	105.9	80°	105.9	130°	115.5	80°	118.3	120°	1,2
Extended fan duct treatment	Nominal	103.0	50°	101.5	120°	110.5	50°	113.6	120°	1,2,3
Long inlet	Nominal	98.7	40°	99.5	120°	104.7*	50°	109.7	120°	1,2,3,4
Fully suppressed	Nominal	95.2*	50°	98.7	110°	103.5*	50°	110.9	130°	1,2,3,4,5
Fully suppressed (wrapped casing)	Nominal	95.2*	50°	99.7	120°	103.1*	50°	110.3	130°	1,2,3,4,5
Maximum fan suppression "hardwall" core exhaust	Nominal	93.8*	50°	99.2	120°	102.8*	50°	109.9	130°	1,3,4,5

* PNL's steadily decrease from the maximum in the aft quadrant. The 50° level is representative of the front quadrant noise.



(1) Fan Frame Treatment

(2) Core Exhaust Treatment

(3) Extended Duct Treatment

(4) Inlet Treatment and Aft Splitter

(5) Three Inlet Splitters

Figure 32. Quiet Engine A, Fully Suppressed Configuration.

large nozzle. Thus, of the three operating lines, that with the nominal nozzle became the most acceptable, acoustically and aerodynamically.

An attempt was made to determine the effect of treating the core exhaust duct by investigating differences between results of the treated fan frame configurations with "hardwall" (Configuration 1 of Figure 32) and "treated" core (Configurations 1,2 of Figure 32) nozzles. Comparisons of PNL directivities and SPL and PWL spectra identified the contribution of noise radiated from the core exhaust to overall engine farfield noise levels. The 200-foot (61-m) sideline perceived noise measurements generally indicated some reductions with the installation of the additional treatment. The perceived noise in both quadrants decreased at low speed and, in the aft quadrant, at 90% fan speed. However, the reductions relative to the "frame-treated" case were only 1.0 PNdB and 0.7 PNdB for the maximum perceived noise at the approach and take-off power settings, respectively, due to high levels of fan noise.

The 120° approach spectra indicated that the broadband noise of the "treated core nozzle" had been reduced a small amount at all frequencies above 1000 Hz. The largest reduction occurred in the 6.3 kHz band, the band containing the low pressure turbine's first stage blade passing frequency. The narrowbands of farfield data at this angle indicated a "haystack" of noise at approximately 6300 Hz for both configurations. Probe data for these configurations, however, indicated that the fundamentals for the low pressure turbine stages were sharp tones in the core exhaust duct. These tones were apparently modulated as they radiated through the coannular jets.

Three Engine A configurations were examined to determine the effect of inlet design on overall engine noise characteristics. Each configuration had the same fan frame acoustic treatment (Element 1) and the core exhaust treatment shown as Element 2 on Figure 32. The inlet designs selected for the comparisons were: (1) a standard reference bellmouth, (2) a thick-lip flight inlet, and (3) a thin-lip flight inlet with blow-in doors. The blow-in doors of the "thin-lip inlet" were fixed to simulate the open position for the duration of the testing at all thrusts. The inlet design had a measurable effect on the overall engine noise signature. The bellmouth produced lower noise characteristics than either of the flight inlets examined, and the thick-lip flight inlet was quieter than the blow-in door inlet. Although these results were based on noise measurements of configurations employing the large fan exhaust nozzle, no difference in the relative magnitudes of noise levels would be anticipated for operation with the nominal exhaust nozzle.

To determine the effect of increasing the fan duct treatment, data from the "extended fan duct treatment" configuration were examined and compared to the "baseline" results. The "extended treatment" configuration incorporated additional suppression material forward and aft of the fan frame treatment. The location of the extended acoustic wall treatment is shown in Figure 32 as Element 3. Evaluation of the acoustic data showed that greater reduction of the maximum levels were attained as thrust was increased up to the take-off thrust level, above which the baseline maximum levels flattened. The baseline maximum levels occurred in the aft quadrant for each thrust. On the other hand, the angles at which the maximum PNL for the "extended duct treatment" configuration occurred shifted from the front quadrant at approach to the aft quadrant at takeoff, the maximum front and aft levels being approximately the same at intermediate thrusts. The reduction in maximum aft quadrant noise due to this treatment was 4 PNdB at approach and 4.3 PNdB at take-off power settings.

To determine the effect of adding splitters to the fan duct, the acoustic test results for two configurations containing splitter treatment variations were examined and compared to the "baseline" results. One configuration ("long inlet") contained aft splitter treatment in the fan exhaust duct - Configuration 1, 2, 3, 4 of Figure 32. The second configuration ("fully suppressed") incorporated fore and aft splitter treatments consisting of the same single splitter in the fan exhaust duct and three splitters in the inlet duct (Configuration 1, 2, 3, 4, 5 of Figure 32). The rear maximum PNL was nearly the same for the "long inlet" and "fully suppressed" configurations - 6 to 8 PNdB below the "frame treatment" configuration. The front levels with the "long inlet" were 6-8 PNdB lower than the "frame treatment" while the "fully suppressed" configuration resulted in a noise reduction of from 9 to 10 PNdB relative to the "frame-treated" data. It should be pointed out that the acoustically treated splitters incorporated in the Engine A inlet and exhaust ducts were not optimized for the aerodynamic environment of these ducts. (See Reference 21). Inserting the aft splitters in the exhaust duct with Mach numbers in excess of 0.5 introduced thrust losses of 4% - 5% at takeoff and probably increased broadband noise generation. It is expected that, if splitter treatment were to be specifically designed for Engine A application (both aerodynamically and acoustically), the resulting engine noise would have been less than the test results indicated. However, these data are representative of the suppression characteristics to be anticipated from such design features.

To determine the amount of noise from the engine casing relative to that from the inlet and the exhaust, the engine with the "fully suppressed" configuration (Configuration 1, 2, 3, 4, 5 of Figure 32) was wrapped with 2 inches (0.51 cm) of Scottfoam and lead vinyl sheets from just aft of the bellmouth to just forward of the fan exhaust. The variation of maximum sideline perceived noise with thrust was basically the same for the "fully suppressed" configuration both with and without the wrapped casing. Any substantial casing radiation would have been indicated by a significant noise reduction when the casing was wrapped in the "fully suppressed" configuration, in that noise propagating from the fan inlet and exhaust had already been significantly suppressed. Only slight casing radiation was evident, in that noise reductions of less than 1 PNdB were observed at take-off and approach power settings.

Further acoustic data comparisons were made with the fully suppressed configuration with treated core nozzle (Configuration 1, 2, 3, 4, 5 of Figure 32) and with "hardwall" core exhaust (Configuration 1, 3, 4, 5 of Figure 32). Comparisons of PNL directivities, SPL, and PWL indicated the effectiveness of the core exhaust portion of the engine acoustic treatment. However, the 200-foot (61-m) sideline perceived noise measurements showed that, contrary to anticipated results, the addition of the core nozzle treatment did not reduce perceived noise levels; and, in fact, there were indications of small increases particularly in the front quadrant. The only noise reduction observed occurred at 120° for the 60% and 70% fan speeds. Again, the residual fan and jet noise precluded measurement of farfield engine noise reduction on a PNL basis. However, narrowband analysis did show decreases in the turbine tone content. Reference 22 contains additional information on these suppressed core data. It was generally concluded that there was little noise contribution from the turbine, even with full suppression of fan noise.

Complete information on the Engine A acoustic results is given in Reference 21. Results of detailed engine acoustics investigations utilizing internal acoustic probes, a broadside directional array, and a nearfield microphone field are given in Reference 22. (See also Section V of this report.)

4. Engine A Flyover Noise Projections

Although Engine A was not designed for actual flight application, an indication of the potential reduction available from the application of technology evolving from this program to actual flight hardware can be obtained by projecting ground static results to in-flight conditions. Effective perceived noise levels (EPNL's) (see Reference 23) were projected for landing approach and take-off flight profiles of a representative older four-engine aircraft of the current civil fleet. The projected EPNL's for aircraft powered by three basic Engine A configurations are compared to the older aircraft levels and to the FAR-36 limits in Table XI.

Although the splitters incorporated in this suppressed configuration were neither aerodynamically contoured nor tailored to the noise signature of Engine A (an existing inlet splitter assembly was utilized), the indicated noise levels are representative of the suppression characteristics of such design features. Note that an economic penalty is associated with any such highly suppressed configuration. (See Reference 24, as well as Section VI of this report.)

The flight noise levels for this class of aircraft were considerably below the FAR-36 requirements. The goals for the Experimental Quiet Engine Program had called for an engine 15-20 PNdB quieter than currently available engines in the same thrust class. Table XI indicates that the predicted acoustic performance of an older, large four-engine aircraft powered by four A-type engines with duct wall treatment shows noise reductions of more than 20 EPNdB relative to the older aircraft and 8 EPNdB relative to FAR-36. Further, the projected noise levels of the aircraft powered by four fully-suppressed Engines A are more than 25 EPNdB below those of the older aircraft and more than 13 EPNdB below FAR-36.

In the flyover noise projections for Engine A, the ground static data were adjusted for the number of engines, the Doppler effect, the range from the airplane to the microphone, and for ground and atmospheric attenuation. In addition, adjustments were made to account for the "relative velocity effect." The SAE method described in AIR 876 (Reference 25) was used to predict the static and flight maximum angle, jet spectra from cycle data for the fan and core jets. These static and flight spectra were arithmetically subtracted from one another. The maximum angle spectral difference was then arithmetically subtracted from the static test results for those angles and over those portions of the test spectra determined to be jet noise. The jet noise portions of the spectra were determined by examining comparisons of the test data and the predicted static jet spectra on an individual basis.

Table XI. Noise Levels at FAR-36 Reference Points (Reference 23), Older Aircraft Configuration with Engine A.

Condition	Landing Approach 1 N.M. (1.853 km) from Runway	Full-Power Takeoff 3.5 N.M. (6.49 km) from Brake Release
JT3D Engine (Reference 26)	118.0 EPNdB	117.0 EPNdB
FAR-36 Limits	106.3 EPNdB	103.5 EPNdB
Quiet Engine A with Fan Frame Treatment (Baseline)*	100.3 EPNdB	98.4 EPNdB
Quiet Engine A with Extended Fan Duct Treatment*	98.0 EPNdB	95.1 EPNdB
Quiet Engine A Fully Suppressed*	92.5 EPNdB	89.2 EPNdB

* Based on projected flight profiles (Reference 27).

5. Engine A Aero Test Results

Detailed performance data were taken with the following configurations:

Type of Inlet	Fan Nozzle Area	Core Nozzle Area
Bellmouth	1790 in^2 (11548 cm^2)	552 in^2 (3561 cm^2)
Bellmouth	1700 in^2 (10968 cm^2)	552 in^2 (3561 cm^2)
Bellmouth	1980 in^2 (12774 cm^2)	552 in^2 (3561 cm^2)
Bellmouth	1790 in^2 (11548 cm^2)	577 in^2 (3723 cm^2)
Thick-Lip	1790 in^2 (11548 cm^2)	577 in^2 (3723 cm^2)
Thick-Lip	1700 in^2 (10968 cm^2)	577 in^2 (3723 cm^2)
Thick-Lip	1980 in^2 (12774 cm^2)	577 in^2 (3723 cm^2)
Thin-Lip w/Blow-in Doors	1980 in^2 (12774 cm^2)	577 in^2 (3723 cm^2)

The engine test data were analyzed and changes made to the Engine A computer "Status Deck" so that it duplicated as closely as possible the measured SLS performance of the engine. Cycle data were then generated with the status deck to cover a wide range of Mach numbers, altitudes, and power settings. These data can be found in Reference 28. With the nominal fan exhaust nozzle installed, overall engine performance (as defined by the status deck) compares to the Experimental Quiet Engine Program Work Statement, as shown in Table XII.

At take-off speed and power, the thick-lip inlet produced 2.9% total-pressure distortion with a pressure recovery of 0.995. The thin-lip, blow-in-door inlet produced 11.2% total-pressure distortion with a pressure recovery of 0.980. Percent distortion here is defined as $(P_{T\ max.} - P_{T\ min.})/P_{T\ max.}$.

The engine run with splitters, three in the inlet and one in the fan exhaust duct, indicated a thrust loss at take-off speed of 5.5%. The major cause of the performance loss was attributed to excessive pressure loss in the fan exhaust duct due to high velocities across the splitter. Fan duct velocity increases of 15% to 20% were estimated with the splitter.

Complete information on Engine A performance is given in Reference 28.

6. Engine C Test Configurations

In order to investigate high fan speed engine characteristics and applicable noise reduction techniques, Engine C was constructed. This engine was based on a new high-tip-speed, single-stage fan, designed at the altitude cruise condition for a corrected tip speed of 1550 ft/sec (472 m/sec), at a bypass pressure ratio of 1.6, and at a corrected fan flow of 915 lbs/sec (415 kg/sec). See Section III of this report (as well as Reference 29) for complete information on the engine.

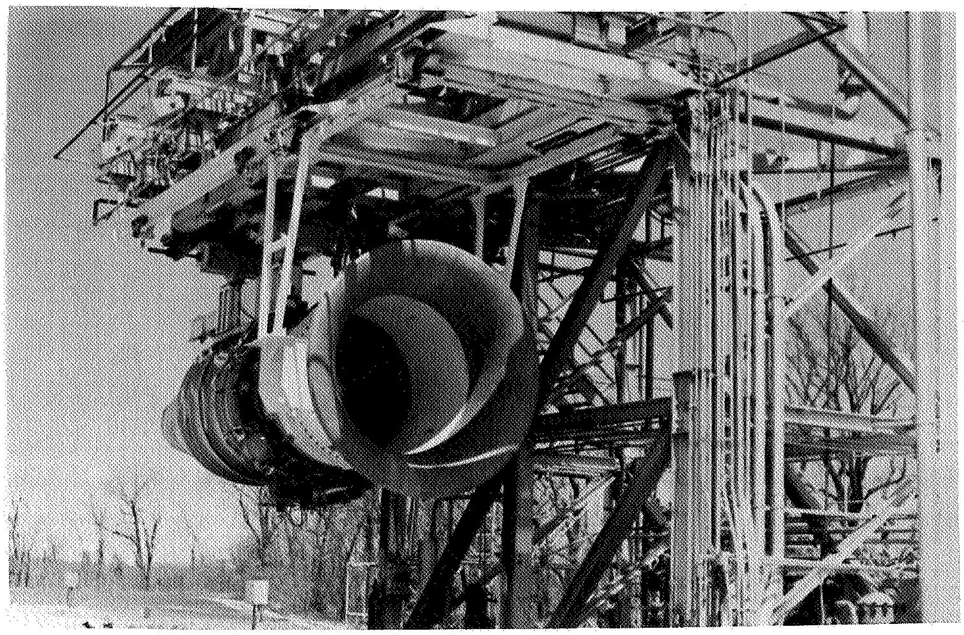
Thirteen configurations were examined to determine the effect of design/treatment variations on the engine system's noise characteristics. In particular the following features were investigated: fan frame treatment, inlet acoustic treatment designs, duct splitter treatment, core engine exhaust treatment, coplanar exhaust nozzles, and engine operating line (various exhaust nozzle sizes). Figures 33 and 34 show two examples of Engine C configurations mounted on the test stand, the "frame treatment" and "fully suppressed" configurations. Details of the configurations are discussed in Reference 29.

7. Engine C Acoustic Test Results

Static engine test data were extrapolated to the 200-foot (61-m) sideline. The Engine C front and aft quadrant maximum perceived noise levels are summarized in Table XIII for the approach and take-off power settings. The engine configurations of Table XIII are coded to those shown in Figure 35 where the various Engine C acoustic treatment configurations are detailed.

Table XII. Overall Performance of Engine A with Nominal Fan Exhaust Nozzle.

Parameter	Engine A	XQEP Work Statement
CRUISE [0.82/35,000 ft (10.67 km)]		
Thrust, lb (N)	4,900 (21,800)	4,900 (21,800)
SFC, hr^{-1}	0.645	0.660
Bypass Ratio	6.14	5 to 6
Overall Pressure Ratio	16.8	18.0 Min.
Fan Bypass Pressure Ratio	1.49	1.5 to 1.6
Combustor Exit Temperature, $T_{3.9}$, ° F (° C)	1919 (1049)	---
Turbine Inlet Temperature, T_4, ° F (° C)	1811 (989)	1775 (969) Max.
TAKEOFF (SLS Standard Day)		
Thrust, lb (N)	22,000 (97,900)	22 000 (97 900)
SFC, hr^{-1}	0.360	0.360
TAKEOFF (0.25/SL)		
Fan Tip Speed, fps (m/sec)	1018 (310.6)	1030 (314.0) Max.
Bypass Jet Velocity fps (m/sec)	821 (250.2)	900 (274.2) Max.
Core Jet Velocity fps (m/sec)	1177 (358.8)	1275 (388.7) Max.
Combustor Exit Temperature, $T_{3.9}$, ° F (° C)	2040 (1116)	---
Turbine Inlet Temperature, T_4, ° F (° C)	1931 (1055)	2000 (1093) Max.



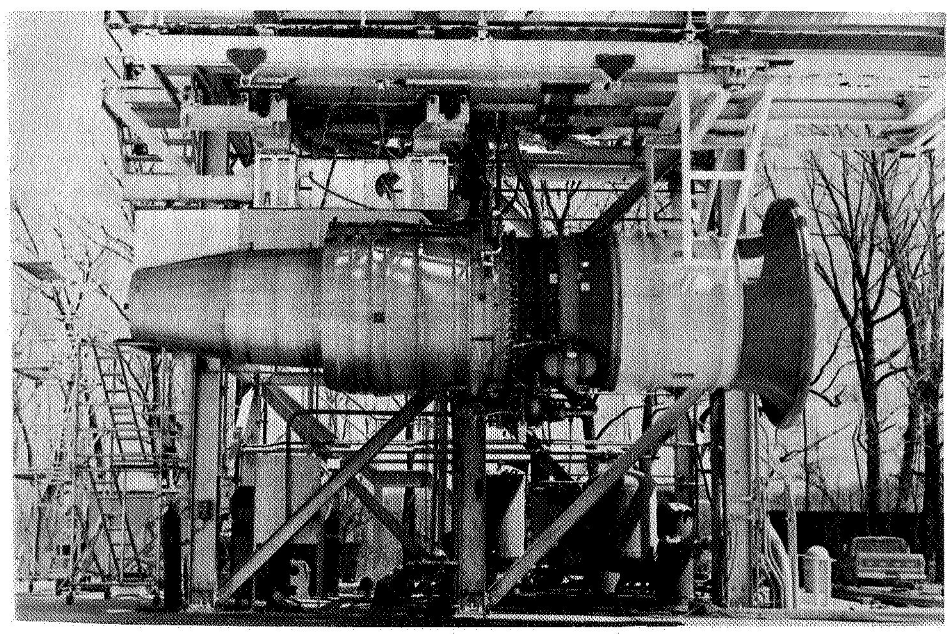


Figure 33. Quiet Engine C, Frame-Treated Configuration on Test Stand.

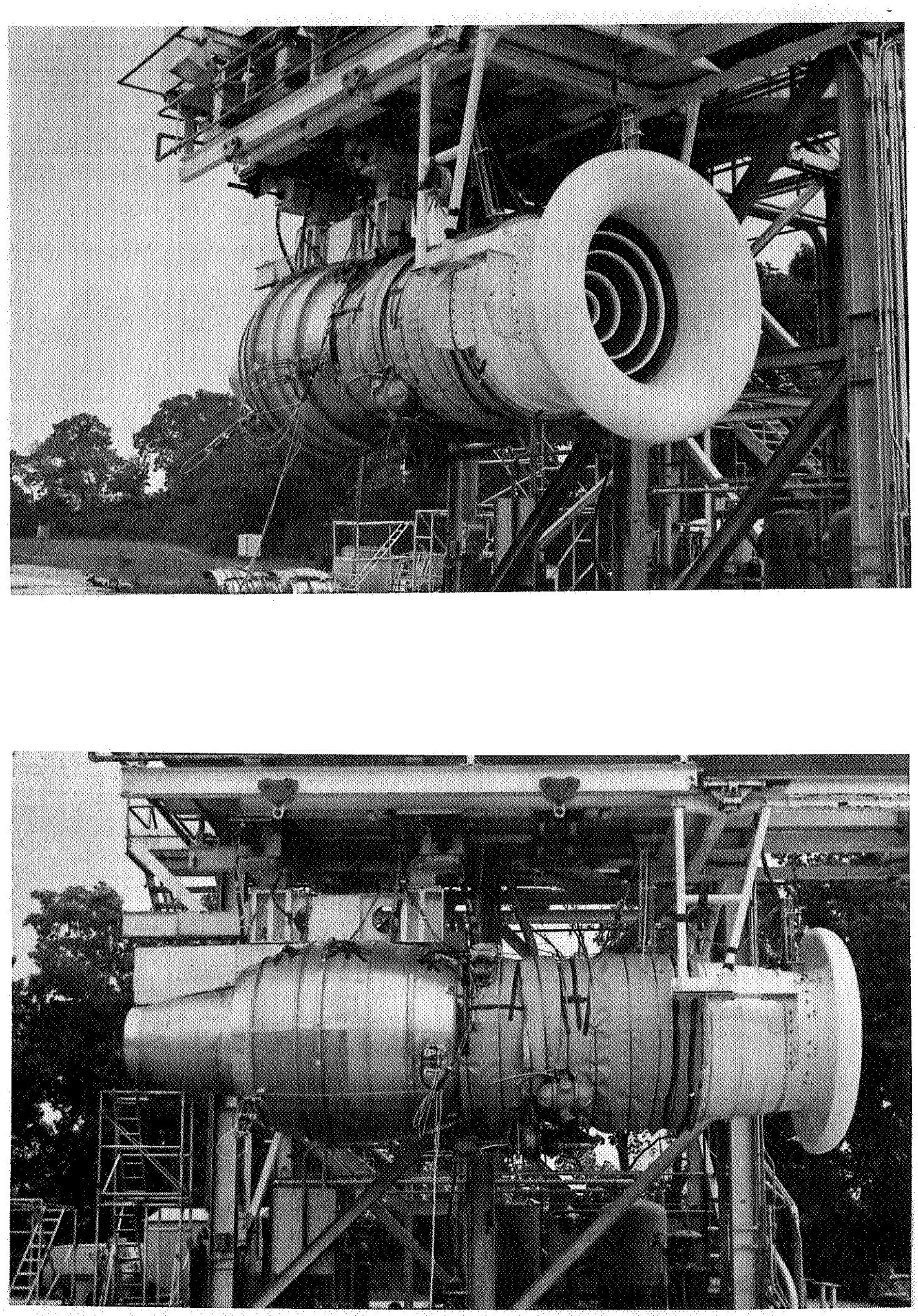
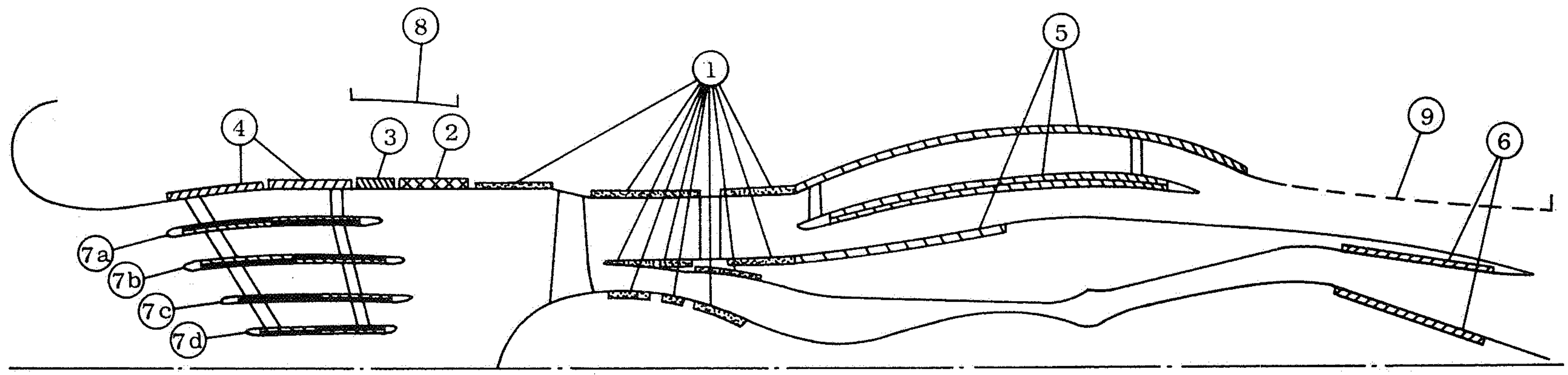


Figure 34. Quiet Engine C, Fully Suppressed Configuration on Test Stand.

Table XIII. Engine C Configurations, Summary of 200-foot (61-m) Sideline Front and Aft Maximum PNL.

Configuration	Approach				Takeoff				Treatment Coded to Figure 35
	Front		Aft		Front		Aft		
	PNL	Angle	PNL	Angle	PNL	Angle	PNL	Angle	
Fan frame treated	107.5	60°	106.3	120°	121.6	50°	118.8	110°	1
Totally suppressed inlet, hard fan exhaust	99.9*	70°	107.3	120°	111.9*	70°	118.8	120°	1,2,3,4,6,7a,7b,7c,7d
Contoured inlet	103.0	50°	102.6	120°	115.5	70°	113.6	110°	1,4,5,6
Long inlet	102.9	50°	101.6	120°	115.2	70°	112.8	110°	1,4,5,6,8
One-splitter inlet	99.9	50°	102.1	120°	112.3	70°	111.2	110°	1,4,5,6,8,7a
Two-splitter inlet	99.8	50°	102.9	120°	110.6	70°	112.0	110°	1,4,5,6,8,7a,7b
Three-splitter inlet	99.6	70°	102.5	120°	110.3	70°	112.1	110°	1,4,5,6,8,7a,7b,7c
Four-splitter inlet	97.5	70°	102.0	120°	108.8	70°	110.4	110 & 120°	1,4,5,6,8,7a,7b,7c,7d
Long inlet with 24" MPT treatment	101.0	60°	101.6	120°	112.5	60°	110.7	120°	1,2,4,5,6
Long inlet with 36" MPT treatment	100.3	50°	102.0	120°	111.1	70°	111.2	110°	1,2,3,4,5,6
Fully suppressed with hard core exhaust	99.1	70°	105.7	120°	108.6	70°	113.2	110°	1,2,3,4,5,7a,7b,7c,7d
Fully suppressed	96.4	70°	101.5	120°	106.5*	70°	110.7	110°	1,2,3,4,5,6,7a,7b,7c,7d
Coplanar nozzle	97.2	70°	102.5	120°	107.0	70°	111.1	120°	1,2,3,4,5,6,7a,7b,7c,7d,9

* PNL's steadily decrease from the maximum in the aft quadrant. The 70° level is representative of front quadrant noise.



(1) Fan Frame Treatment

(2) MPT Treatment - Long

(3) MPT Treatment - Short

(4) Contoured Inlet Treatment

(5) Fan Exhaust Duct Treatment and Low-Mach-No. Exhaust Splitter

(6) Core Exhaust Treatment

(7a) (7b) (7c) (7d) Four Ring Splitter System

(8) Hardwall Inlet Extension Section

(9) Extended Fan Exhaust Duct - Coplanar Nozzle

Figure 35. Quiet Engine C, Fully Suppressed Configuration.

The "Baseline" Engine C configuration investigated contained acoustic treatment in the fan frame and in the compressor inlet. Details of the acoustic wall treatment for this "frame-treated" configuration are shown in Figure 35 (Configuration 1). Evaluation of the "frame-treated" acoustic data at the 200-foot (61-m) sideline shows that the perceived noise at each angle generally increased with successively higher fan speeds, although the front quadrant noise levels at 80% were very similar to those at 90% fan speed. At each speed the maximum perceived noise occurred in the front quadrant at either 50° or 60°. The comparison of maximum perceived noise in the front quadrant and in the aft quadrant likewise indicated that the noise levels were higher in the front quadrant at all fan speeds. While the aft maximum levels increased smoothly between the approach and take-off power settings, the maximum levels in the front increased sharply between 12,500 pounds (55,656 N) of thrust and 16,300 pounds (72,535 N) of thrust. At these data points the engine thrust levels corresponded to 70% and 80% fan speeds, respectively. Onset of the supersonic phenomenon of multiple pure tones (MPT's) occurred between these points. The MPT's characteristically make a major contribution to noise at frequencies below the blade passing frequency (at multiples of the fan rotor shaft revolutions) when the fan rotor tip relative Mach number exceeds unity.

Engine C was tested with two additional fan exhaust nozzles to investigate the effect of the variation of the engine operating line on the engine's performance and acoustic characteristics. The design area of the fan exhaust nozzle was 1539 square inches (0.99 m^2). The other nozzles were 10% smaller and 10% larger in area. The "frame-treated" configuration was tested with each of the three nozzles. Only small changes in the engine's acoustic characteristics due to the exhaust nozzle changes were found.

Substantial acoustic treatment was added to the basic engine configuration in order to suppress fan noise. The goal of the acoustic treatment design was to achieve noise levels which were similar in magnitude to those recorded for the "fully-suppressed" Engine A. A contoured inlet which incorporated single-degree-of-freedom (SDOF) wall treatment replaced the basic fan inlet. The contoured inlet included a four-ring splitter system. (See Reference 29). Two casings with thick treatment for MPT suppression were also added forward of the fan frame. In addition, the fan duct was replaced with a long exhaust duct which incorporated an exhaust splitter and extended SDOF acoustic wall treatment. The exhaust duct was designed for low Mach number flow in order to increase the effectiveness of the acoustic treatment and to reduce flow scrubbing noise. The engine was also wrapped with lead vinyl and polyurethane foam to prevent casing radiation. Further details of the acoustic treatment of the totally suppressed configuration are presented in Figure 35 (Configuration 1, 2, 3, 4, 5, 6, 7a, 7b, 7c, 7d).

Large reductions of perceived noise were achieved at each engine speed, relative to the "baseline" noise levels for the "fully-suppressed" configuration. In particular, the greatest reductions relative to "frame-treated" noise levels were attained in the front quadrant. The angles of maximum perceived noise shifted from 50° to 60° for the "baseline" to 110° to 120° for the "fully-suppressed" configuration. At the approach power setting (60% fan speed), significant reductions of the "baseline" noise levels for each angle were achieved in both the front quadrant, from 7.5 to 12.6 PNdB, and in the rear quadrant, from 4.5 to 7.3 PNdB. Further noise reduction was prevented by jet, turbine, and fan duct broadband noise. The maximum perceived noise, which occurred at 60° for the baseline, was suppressed 12.1 PNdB by the addition of the full acoustic treatment. However, since less reduction was attained at the adjacent angles, the forward "maximum" angle for the "fully-suppressed" configuration shifted to 70°, and the "maximum-to-maximum" reduction was only 11.1 PNdB.

Large noise reductions were also achieved at all angles at takeoff with the "fully suppressed" configuration. The greatest reductions were attained in the front quadrant; 14 PNdB suppression or more was found for each angle from 20° to 70°. The greatest suppression, 17.2 PNdB, occurred at 50°. However, the "maximum-to-maximum" reduction in the front quadrant was only 15.1 PNdB. The amount of reduction demonstrated for each angle decreased from the 50° angle to 150° where the "frame-treated" level was suppressed by 4.6 PNdB. At 110°, the "frame-treated" aft maximum PNL was reduced 8.1 PNdB to 110.7 PNdb. Further aft noise reduction was prevented by jet and fan duct broadband noise. Thus, large reductions of the baseline noise levels were achieved with the full acoustic treatment for Engine C. The greatest amounts of suppression were achieved in the front quadrant. The MPT's and the fundamental and fan harmonics characteristic of the "frame-treated" configuration were virtually eliminated from the "fully suppressed" results. However, turbine/core-related noise appeared to have held the overall engine levels up at the approach power setting. It was concluded that noise levels no greater than those attained with suppressed, lower-tip-speed fan engines were achieved with suppressed higher-tip-speed fan engines.

The noise reduction aspects of the fan exhaust duct of the "fully suppressed" engine were features of particular interest. The conventional bypass duct had been completely replaced by an exhaust duct and splitter assembly which was designed for low Mach number flow over the acoustically treated walls and splitter. The contribution of the low Mach number exhaust duct design was investigated by testing an engine configuration with the conventional, untreated bypass duct while the inlet was totally suppressed (Configuration 1, 2, 3, 4, 6, 7a, 7b, 7c, 7d of Figure 35). The 200-foot (61-m) sideline perceived noise levels of the totally suppressed inlet, hard fan exhaust configuration (referred to as the "suppressed inlet") were compared to the noise characteristics of the "fully suppressed" configuration in order to evaluate the effectiveness of the new bypass duct design. Test results demonstrated that suppression of fan exhaust noise by the splitter and extended wall treatment occurred at every angle along the sideline. In other words, significant acoustic energy from the fan exhaust was radiating into the front quadrant. These reductions were evident at all speeds. At the approach power setting, the addition of the splitter and extended treatment resulted in suppressions of 2 to 4 PNdB in the front quadrant and 5 to 8 PNdB in the aft quadrant. The spectral comparison at 70° indicated that the "fully suppressed" SPL's were lower at all frequencies. At 120°, a 5-1/2 PNdB reduction was attained with the splitter and extended wall treatment. The fan exhaust noise appeared to have been reduced to the point where perceived noise was apparently controlled by a core noise floor. Noise suppression of 5 dB or more was achieved from 1250 Hz to 5000 Hz, with 10 dB attained in the 4000 Hz band and 7-1/2 dB in the 5000 Hz band.

The comparison at the take-off power setting, 90% speed, indicated that the installation of the low Mach number splitter and extended wall treatment yielded 3-1/2 to 5-1/2 PNdB reduction in the front quadrant and 7-1/2 to 9 PNdB reduction at the aft angles. Without the bypass duct treatment, fan fundamental and harmonic tones as well as broadband noise were radiated from the fan exhaust. Both the blade passing frequency tone and higher broadband levels were radiated to the forward angle (70°) for the suppressed inlet configuration. At the aft angle, 110° from the inlet, the fundamental and second harmonic tones were very prominent. The blade passing frequency tone was about 14 dB higher than the "fully suppressed" level, while the second harmonic was 11 dB higher without the exhaust duct suppression. The high frequency broadband noise was also significantly higher for the "suppressed inlet" configuration. A comparison of the maximum perceived noise levels demonstrated that a reduction of 4 to 9 PNdB was achieved by the addition of the low Mach number splitter and treated bypass duct assembly.

Part of the systematic approach to determine the individual contributions of the engine acoustic treatment was to investigate the characteristics of the noise suppression achieved with the inlet splitters. The four-ring inlet splitter system was designed so that the splitters could be individually removed, starting with the innermost splitter. In this fashion it was possible to examine the noise characteristics for four, three, two, and one splitters as well as for no splitter. Thus, referring to Figure 35, tests were performed with Configuration 1, 4, 5, 6, 8, as well as with configurations including Element 7a; 7a and 7b; 7a, 7b, and 7c; and 7a, 7b, 7c, and 7d.

Details of the splitter system are presented in Figure 35. The splitter and inlet wall treatment consisted of two SDOF designs which utilized different treatment thicknesses for maximum suppression at different frequencies. These two designs were positioned such that opposing passage surfaces had similar treatment. Note that the inlet with four splitters differed from the "fully suppressed" configuration, in that a hardwall spool replaced the deep treatment for MPT suppression. In this manner it was possible to determine the amount of MPT suppression attained with the splitters.

In order to evaluate the 200-foot (61-m) sideline results, the directivity and spectral comparisons for the inlet variations were considered as suppression differences as well as absolute noise levels. The suppression differences were computed relative to the "no splitter" results. The perceived noise directivities for the various splitter configurations showed that without splitters the noise levels showed forward dominance. With the addition of one or more inlet splitters, however, the maximum PNL generally shifted to an aft angle.

The greatest suppression increment attained by the addition of a splitter was from no splitters to one splitter. Significant reductions were attained from 30° to 90° with the outermost splitter. The addition of the second and third splitters produced far less additional suppression at the approach and take-off power settings, although gains at the 70% and 80% speeds were noteworthy. The addition of the fourth splitter yielded a definite improvement at each forward angle for all speeds. The single splitter produced no noise reduction at the extreme forward angles (10° and 20°). Addition of the second and third splitter produced successively more suppression at these angles. However, the largest additional suppression due to the fourth splitter was attained at these angles. These results suggest that the perceived noise at the forward angles was primarily controlled by noise propagating through the center of the duct. In contrast, treatment in the outer portion of the flowpath (single splitter) had the greatest effect on the engine noise levels measured from 40° to 80°.

The spectral comparisons of the splitter configurations showed that, for the approach power setting at 50°, a progressive spectral suppression occurs with increasing number of splitters for the 1000-Hz band and above. In particular, large reductions of the fundamental and second harmonic were achieved with both three splitters and with four splitters. The comparison further indicated that a nearly constant noise reduction was attained with the single splitter for bands from 1000 Hz to 5000 Hz. The spectra at 120° were generally slightly higher than the "no splitter" configuration. This was especially true at the higher frequencies for the configurations with two and three splitters.

At the take-off power setting, the spectra in both the front and aft quadrants were dominated by the 400-Hz MPT's. Large amounts of suppression were achieved at 70° by the addition of splitters. The amount of suppression generally followed the same pattern as observed at the approach power setting. The frequency range of the suppression broadened at takeoff, and the amount of suppression attained with the outermost splitters increased at the front quadrant angle. The "long inlet" with 36-inch (91.5-cm) MPT treatment incorporated 73.3 inches (186.2 cm) more inlet wall treatment than the "baseline" inlet. To determine the effectiveness of this additional wall treatment and length, the engine was tested with segments of this treatment removed. Four variations of wall treatment were examined. The entire wall treatment used for the total engine suppression, in addition to the frame treatment (Element 1 of Figure 35), consisted of: 36 inches (91.5 cm) of deep treatment for MPT suppression constructed of a 24-inch (61-cm) section (Element 2) and a 12-inch (30.5-cm) section (Element 3); and a 37.3-inch (94.7-cm) contoured section of mixed thickness treatment (Element 4).

The following combinations were tested: the contoured section by itself (Configuration 1, 4, 5, 6 of Figure 35), the contoured section plus a 24-inch (61-cm) hardwall spool to increase the inlet length (Configuration 1, 4, 5, 6, 8), the contoured section plus the 24-inch (61-cm) treated section (Configuration 1, 2, 4, 5, 6) and the contoured section plus both the 24-inch (61-cm) and the 12-inch (30.5-cm) sections with thick treatment (Configuration 1, 2, 3, 4, 5, 6).

The comparisons of the perceived noise directivities for these inlet configurations showed that very little effect of the additional 24 inches (61 cm) of hardwall length could be observed for the "long inlet" configuration compared to the results for the "Contoured Inlet" with the exception of the 80% speed. The inlet with 24 inches (61 cm) of thick treatment for MPT suppression provided the largest increment of suppression and did so over a wide range of angles. The effect of the additional 12 inches (30.5 cm) of thick treatment was most evident in the front angles of 10° to 60°, although at 70% speed sizeable reductions were attained to 90° with added treatment. Generally 3 to 6 PNdB suppression of the front quadrant noise levels were attained with the full wall treatment relative to the contoured inlet levels.

The approach spectra at 50° indicated that the fundamental, although reduced about 3 dB, continued to control perceived noise with the full wall treatment. However, the broadband noise and the bands containing the fan harmonics were reduced from 3 to 4 dB by both configurations with MPT treatment. At 120°, the contoured inlet spectrum was reduced a small amount by each of the other configurations.

At the take-off power setting, a significant reduction of MPT noise was achieved with the thick wall treatment. The MPT's at 400 Hz and 500 Hz were reduced approximately 12.5 dB at 50° and 9 dB at 110° relative to the "Contoured Inlet" configuration. The suppression due to the thick treatment extended over a wide range of frequencies (from 315 Hz to 10 kHz). At 50°, the additional 12 inches (30.5 cm) of treatment produced an extra 2 to 4 dB suppressed over most of this range. It was concluded that multiple pure tone (MPT) noise can be effectively suppressed (although not completely eliminated).

The farfield results for the "Fully Suppressed" configuration (Configuration 1, 2, 3, 4, 5, 6, 7a, 7b, 7c, 7d of Figure 35) indicated that an apparent core noise floor held up the approach aft quadrant noise levels, despite the inclusion of core exhaust treatment (Element 6 of Figure 35) in the engine. To determine the effectiveness of the acoustic treatment in the core exhaust duct, these panels were replaced by hardwall pieces for one set of tests. Both of the configurations incorporated a contoured inlet with a four-ring splitter system, thick inlet wall treatment for MPT suppression, fan frame treatment, and a low Mach number splitter and extended wall treatment in the bypass duct (Configuration 1, 2, 3, 4, 5, 7a, 7b, 7c, 7d of Figure 35). In this fashion, fan noise was highly suppressed so that core noise suppression could be observed.

The perceived noise results indicated that the engine noise levels were reduced from 2 to 4-1/2 PNdB at angles of 80° through 130° by the installation of the SDOF wall treatment in the core exhaust duct. The maximum reduction of perceived noise occurred at 90°. At the angle of the forward maximum PNL (70°), the approach perceived noise of the fully suppressed engine was 2-1/2 PNdB lower than that of the "hard core" configuration. Addition of core treatment reduced the engine noise from 2.5 kHz to 10 kHz at 70°. The amount of noise reduction at this angle suggests core noise radiated from the aft to the front quadrant. The spectral comparison at 120° showed that the suppressed fan levels were reduced in the range of 2 kHz to 10 kHz by the core treatment.

The turbine tones were suppressed approximately 6 to 7 dB by the core treatment. In addition, the noise levels within the 4 and 5 kHz bands were substantially reduced. It was thus apparent that the maximum level at approach was controlled by noise radiated through the core exhaust duct and not by fan noise.

Generally a half to one PNdB less reduction was attained at the take-off power setting than at approach. The spectra for the front and aft angles of maximum perceived noise showed that at 70°, the suppressed fan spectrum was reduced from 2 to 4-1/2 dB for 1/3-octave bands above 1600 Hz by the addition of the core duct treatment. At 110°, the hard core duct noise levels were reduced from 3 dB to 7 dB, the amount of suppression increasing from 3.15 to 10 kHz. Both configurations produced the same noise levels at the lower frequencies for 70° and 110°. The reduction of the maximum aft quadrant noise levels due to the addition of the core exhaust treatment showed that reductions of from 2 to 4 PNdB were indicated, decreasing with increasing power setting. This trend reflects the relative contribution of core noise to the overall engine noise levels.

The fully suppressed configuration was also modified to determine the acoustic effects of coplanar jet exhausts. The bypass duct was extended 53 inches (134.6 cm) without any additional acoustic treatment (Configuration 1, 2, 3,4, 5, 6, 7a, 7b, 7c, 7d, 9 of Figure 35). The fan discharge nozzle area was designed to be approximately the same as that of the "Fully Suppressed" engine. In all other aspects the "Fully Suppressed" configuration was unchanged.

Comparison of the 200-foot (61-m) sideline PNL directivities for the coplanar and noncoplanar nozzle, "fully suppressed" engine configurations indicated very small differences at approach. The perceived noise measured for the coplanar configuration was about a half to one PNdB higher at 70° and 120°. However, an observation can be made concerning the turbine tones of these two configurations. The second-stage tone was much sharper and 7 dB higher for the configuration with the coplanar nozzle. Likewise, the first-stage tone was at least 5 dB higher than the fully suppressed tone which occurred at 6150 Hz. However, the turbine treatment in the core exhaust duct was exactly the same for these two configurations. The shape of the second stage tone for the noncoplanar configuration suggests that it may have been modulated, dispersing the noise energy associated with this tone over a band of frequencies. It may further be speculated that such modulation took place within the mixing region of the two jets and that the characteristics of the turbine noise radiation were altered when the mixing characteristics were changed by the extended fan duct. The lack of PNL change despite the change in the character of the turbine noise resulted from the fact that the 1/3-octave band levels of the bands containing the tones did not change even though the narrowband tones did change. This suggests that whatever the modulation mechanism is, it is conservative, i.e., no change in energy takes place.

Complete information on these acoustic results is given in Reference 29. Results of detailed engine acoustic investigations utilizing internal acoustic probes, a broadside directional array, and a nearfield microphone field are given in Reference 22 (see also Section V of this report).

8. Engine C Flyover Noise Projections

Although Engine C was not designed for actual flight application, an indication of the potential reduction available from the application of technology evolving from the program to actual flight hardware can be obtained by projecting ground static results to in-flight conditions. Effective perceived noise levels (EPNL's) were projected for landing approach and take-off flight profiles of a representative older four-engine aircraft of the current civil fleet. The projected EPNL's for aircraft powered by three basic Engine C configurations were compared to current older aircraft levels and to the FAR-36 limits as shown in Table XIV.

The projected Engine C flight noise levels for this class of aircraft were considerably below the levels of currently available engines which power the older aircraft. The Engine C baseline effective perceived noise levels were 13.5 and 11.1 EPNdB less than the JT3D levels for the approach and take-off power settings, respectively. The four-engine older-aircraft FAR-36 requirements were nearly achieved with the fan frame treatment alone. The approach level was 1.8 EPNdB less than the FAR-36 limit, while the take-off level exceeded the limit by 2.4 EPNdB. The flyover noise projections for Engine C utilized the same "relative velocity effects" correction as in the case of Engine A (see Section IV.B.4 of this report).

Table XIV. Noise Levels at FAR-36 Reference Points, Older Aircraft Configuration With Engine C (Reference 23).

Condition	Landing Approach 1 N. Mile from Runway (1.853 km)	Full-Power Takeoff, 3.5 N. Mile from Brake Release (6.486 km)
JT3D Engine (Reference 26)	118.0 EPNdB	117.0 EPNdB
FAR-36 Limits	106.3 EPNdB	103.5 EPNdB
Quiet Engine C with Fan Frame Treatment (Baseline)*	104.5 EPNdB	105.9 EPNdB
Quiet Engine C with Extended Fan Duct Treatment with Aft Splitter*	97.4 EPNdB	94.6 EPNdB
Quiet Engine C "Fully Suppressed*"	93.6 EPNdB	87.0 EPNdB
*Based on projected flight profiles (Reference 27)		

The predicted acoustic performance presented in Table XIV indicates that an older aircraft powered by four C-type engines with fan duct wall treatment and aft splitter would produce noise reductions of more than 20 EPNdB relative to the older aircraft and 8 EPNdB relative to FAA noise regulations. Further, the projected noise levels of the older aircraft with four "fully suppressed" Engines C were more than 24 EPNdB below those of the existing older aircraft and more than 12 EPNdB below FAR-36. (Note that there is an economic penalty associated with the maximum feasible noise reduction which can be significant. See Reference 24, as well as Section VI of this report.

9. Engine C Aero Test Results

Detailed performance data were taken on Engine C with a bellmouth inlet and three fan nozzles with areas of 1385 in^2 (8936 cm^2), 1539 in^2 (9930 cm^2), and 1695 in^2 (10,936 cm^2). The core nozzle area remained at 850 in^2 (5483 cm^2). The engine test data were analyzed and changes made to the Engine C computer "Status Deck" so that it duplicated as closely as possible the measured SLS performance of the engine. Cycle data were then generated with the Status Deck to cover a wide range of flight Mach numbers, altitudes, and power settings. These data can be found in Reference 30. The engine was also tested with several combinations of splitters in the inlet and fan duct and a coplanar exhaust nozzle system.

With the nominal fan nozzle installed, Engine C performance (as defined by the Status Deck) compares to the Experimental Quiet Engine Program work statement as shown in Table XV.

The flow-speed characteristic of the fan on the engine duplicated the results obtained in the fan test facility. Bypass efficiency, which appeared to be low, was compensated by the hub efficiency which was higher. Efficiency levels in the bypass reached about 82%. Hub efficiency was not measured directly but, based on instrumentation at the core engine inlet, appeared to be above 86%.

The low pressure turbine met its performance requirements. A comparison between test data and the turbine design point follows:

	LP Turbine Design Point	Engine Test Data
$N/\sqrt{T_{54}}$, RPM/$\sqrt{°R}$ (RPM/$\sqrt{°K}$)	115.5 (155.3)	114.2 (153.5)
$\Delta h/T_{54}$, Btu/lb°R (Joules/kg°K)	.0576 (241.2)	.0584 (244.5)
P_{54}/P_{56}	2.88	3.05
Efficiency	.903	.901
Stage Loading, $gJ\Delta h/2U_p^2$	1.035	1.073

Complete information on Engine C performance is given in Reference 30.

Table XV. Overall Performance of Engine C with Nominal Fan Exhaust Nozzle.

Parameter	Engine C	XQEP Work Statement
CRUISE [0.82/35,000 ft (10.67 km)]		
Thrust, lb (N)	4900 (21800)	4900 (21800)
SFC, hr^{-1}	0.673	0.660
Bypass ratio	5.31	4.5 to 6.0
Overall pressure ratio	18.3	18.0 minimum
Fan bypass pressure ratio	1.66	1.5 to 1.6
Combustor exit temperature, $T_{3.9}$, ° F (° C)	1886 (1031)	---
Turbine inlet temperature, T_4, ° F (° C)	1784 (975)	1775 (969) maximum
TAKEOFF (SLS standard day)		
Thrust, lb (N)	22000 (97900)	22000 (97900)
SFC, hr^{-1}	0.382	0.370
TAKEOFF (0.25/SL)		
Fan tip speed, fps (m/sec)	1384 (421.8)	1400 (426.7) maximum
Bypass jet velocity, fps (m/sec)	903 (275.2)	900 (274.2) maximum
Core jet velocity, fps (m/sec)	862 (262.7)	1275 (388.7) maximum
Combustor exit temperature, $T_{3.9}$, ° F (° C)	2024 (1108)	---
Turbine inlet temperature, T_4, ° F (° C)	1920 (1050)	2000 (1093) maximum

Maximum front end noise suppression required the design of the new contoured inlet with acoustic splitters installed. The inlet throat was sized at cruise [0.82 flight Mach number, 35,000 feet (10,668 m) altitude, 4900 pounds (21,800 N) thrust] to have an average throat Mach number of 0.75. The corresponding throat Mach number at takeoff was 0.58. The equivalent diffuser half angle was 7-1/2°, and the ratio of the highlight to throat diameter (D_{HL}/D_{throat}) was 1.14. The four splitters were positioned along streamlines identified as the 0.25 flight Mach number take-off condition. Engine testing with 1, 2, and 3 splitters was run with a 12-inch section between the splitters and with the fan face removed. Test data indicated that the resulting 12-inch (30.48-cm) shift caused a flow redistribution and an accompanying loss in engine performance. To keep fan duct pressure loss to a reasonable level (with a splitter in place), increase the effectiveness of the acoustic treatment, and lower the fan duct scrubbing noise, new hardware was procured to lower the fan duct Mach number. The core cowl was unchanged, with an area increase in the redesigned fan cowl. The splitter and fan cowl design provided for a 60/40 flow split between the outer and inner flowpaths, respectively, with a total-pressure loss in the fan duct and nozzle of approximately 1.5%. Total-pressure traverses behind the splitter and engine thrust measurements substantiated the estimated pressure loss.

10. Engine Testing at NASA

Upon completion of aerodynamic and acoustic testing at the Peebles Test Facility, the engines were delivered to the NASA-Lewis Research Center. There further aerodynamic and acoustic evaluation was carried out, including the installation on Engine A of a Boeing flight-type acoustic nacelle (see References 9 and 31). These engines will be used as research vehicles in the NASA program aimed at aircraft noise reduction. General Electric has designed and fabricated additional hardware for this program, including a "near-sonic" inlet and an advanced treated core suppressor which will be evaluated on Quiet Engine C.

SECTION V

TURBINE NOISE SUPPRESSION

A. BASIS OF THE TURBINE NOISE SUPPRESSION PROGRAM

Although the initial thrust of the Experimental Quiet Engine Program was directed to the fan component as the principal noise source it was recognized that the turbine would become an important noise source when fan noise was suppressed. Accordingly, the turbine noise suppression program was added to the overall effort.

The objective of the turbine noise suppression program was to determine turbine noise characteristics, to investigate potential suppression materials, and to identify the treatment configuration design for optimum suppression of turbine-radiated noise in Quiet Engines A and C. The result of the program was the measurement of the reduction in engine noise resulting from the core exhaust treatment in the two test engines.

B. ACOUSTIC TREATMENT EVALUATION

1. Test Facilities

A high temperature, rectangular acoustic duct test facility (See Reference 22) was used in evaluating transmission loss characteristics for various treatment configurations. Two 18.0-inch (45.7-cm) long rectangular test sections were capable of receiving acoustic test panels of 2.5-inches (6.35-cm) maximum depth. A Hartmann noise generator was employed as a noise source. The acoustic impedance was predicted or measured for all treatment configurations that were selected to be evaluated in the high temperature acoustic duct test facility (See Reference 22). Impedance measurements were made using a high intensity impedance tube facility. In addition, the effect of high temperatures, as encountered in the core nozzle region of an engine, on the dc flow resistance of a perforated plate was investigated in a high temperature dc flow resistance facility (see Reference 22).

2. Treatment Configurations

The three different types of treatment evaluated for turbine noise suppression were designated as follows:

- Single-degree-of-freedom (SDOF)
- Multiple-degree-of-freedom (MDOF)
- Bulk absorbers

A single-degree-of-freedom (SDOF) liner system is based on a simple Helmholtz resonator concept with one cavity. Thus, excluding wave resonance, it exhibits only one resonance or one tuning frequency. A multiple-degree-of-freedom (MDOF) liner system is based on a scheme which interconnects several cavities. Thus, it exhibits several resonant frequencies which can give the appearance of a wider bandwidth liner with properly chosen cavity relationships and internal resistances. Twenty four SDOF systems were examined. Five MDOF systems were evaluated (three triangular-core systems and two double-sandwich systems). Four bulk absorber systems were evaluated for comparison purposes.

3. Acoustic Treatment Characteristics

Reference 22 contains full acoustic data for all treatment configurations evaluated. The configurations were rated acoustically by calculating the potential PNL reductions in the engine. The required spectra were derived by applying measured duct transmission loss values to the predicted turbine noise spectra.

C. ENGINE TREATMENT SELECTION

1. Engine A

The turbine treatment for Engine A was selected on the basis of predicted acoustic characteristics, manufacturing technique requirements, cost, weight, reliability, and maintainability. Results of this evaluation led to the selection of the double-sandwich MDOF treatment configuration.

2. Engine C

The turbine treatment for the Engine C vehicle was based on an evaluation similar to that made for Engine A. The suppression predictions for Engine C, as for Engine A, were calculated by applying duct transmission loss values to the predicted turbine noise spectrum.

The ΔPNL values were calculated for Engine C for a number of different treatment configurations. The double sandwich gave the optimum suppression (about 12 PNdB) however, the SDOF systems were the most favorable from the view point of cost and weight considerations. Since the difference in the suppression between the configurations was small, it was felt that all of the configurations would produce nearly the same farfield suppression. Therefore, the SDOF treatment was selected for Engine C.

Complete details of the core exhaust treatment selection for Engines A and C are given in Reference 22.

D. ENGINE HARDWARE DESIGN

1. Engine A

The Engine A suppressed exhaust nozzle design consisted of an inner and outer support shell into which panels were bolted which formed the actual nozzle flowpath. Two sets of panels were constructed. One consisted of a support frame with solid face sheets, which served as a hardwall baseline nozzle. The second set was the double-layer brazed honeycomb acoustic configuration, "Double Sandwich II." An Engine A exhaust nozzle cross section with the "Double Sandwich II" acoustic panels in place, showing the basic construction as well as acoustic treatment length, is shown in Figure 36.

2. Engine C

Two separate suppressed exhaust nozzles were constructed for Engine C. One was the hardwall baseline nozzle which consisted of an inner and outer exhaust cone. The second nozzle was the acoustically treated flightweight version where single-layer brazed honeycomb had been selected for the treatment. Manufacture of a single-layer brazed honeycomb continuous shell was within the state of the art and, thus, this type of construction was selected. Figure 37 shows a cross section of the Engine C acoustic nozzle and defines treatment length.

E. ENGINE TESTING

1. Special Instrumentation

In connection with the turbine noise suppression program, additional special instrumentation was used in order to assess performance of the selected acoustic treatment configurations. The special instrumentation consisted of acoustic probes in the core exhaust nozzles of the engines, a nearfield microphone field, and a special "Directional Acoustic Array."

The directional acoustic array consisted of a rigid beam containing 14 equally spaced microphones and associated shading and summing electronics. The directional array is, in essence, a highly directional microphone system encompassing a frequency range from 1.25 kHz to 6.3 kHz, and a narrow beam width and sufficient included angle between on-axis and off-axis lobes to be able to separate closely spaced noise sources. Thus, it can be used to identify the source contributing at a particular angle, e.g., inlet, fan aft, core aft, casing-radiated noise. The array was positioned on Engine A at angles between 50° and 130°, measured from the inlet at a nominal distance of 100 feet (30.5 m) from the fan rotor. At each of these positions, the array was directed at nine engine locations and the output signal was recorded. The array was positioned on Engine C at similar angles at a nominal distance of 100 ft (30.5 m) from the fan rotor. The array narrowband output was analyzed with a 20 Hz bandwidth filter over the frequency range of 1.25 to 6.3 kHz. Amplitudes for the array directed at each engine source were tabulated, and the array characteristics were applied to obtain the source component levels.

Six nearfield microphones were positioned near Engine A on an 8-foot (2.44-m) sideline. They were placed at the height of the engine centerline and pointed upward (grazing incidence). The nearfield microphones on Engine C were placed on a 6-foot (1.83-m) sideline. Nearfield data from the six microphones were recorded simultaneously. Results are discussed in Reference 22.

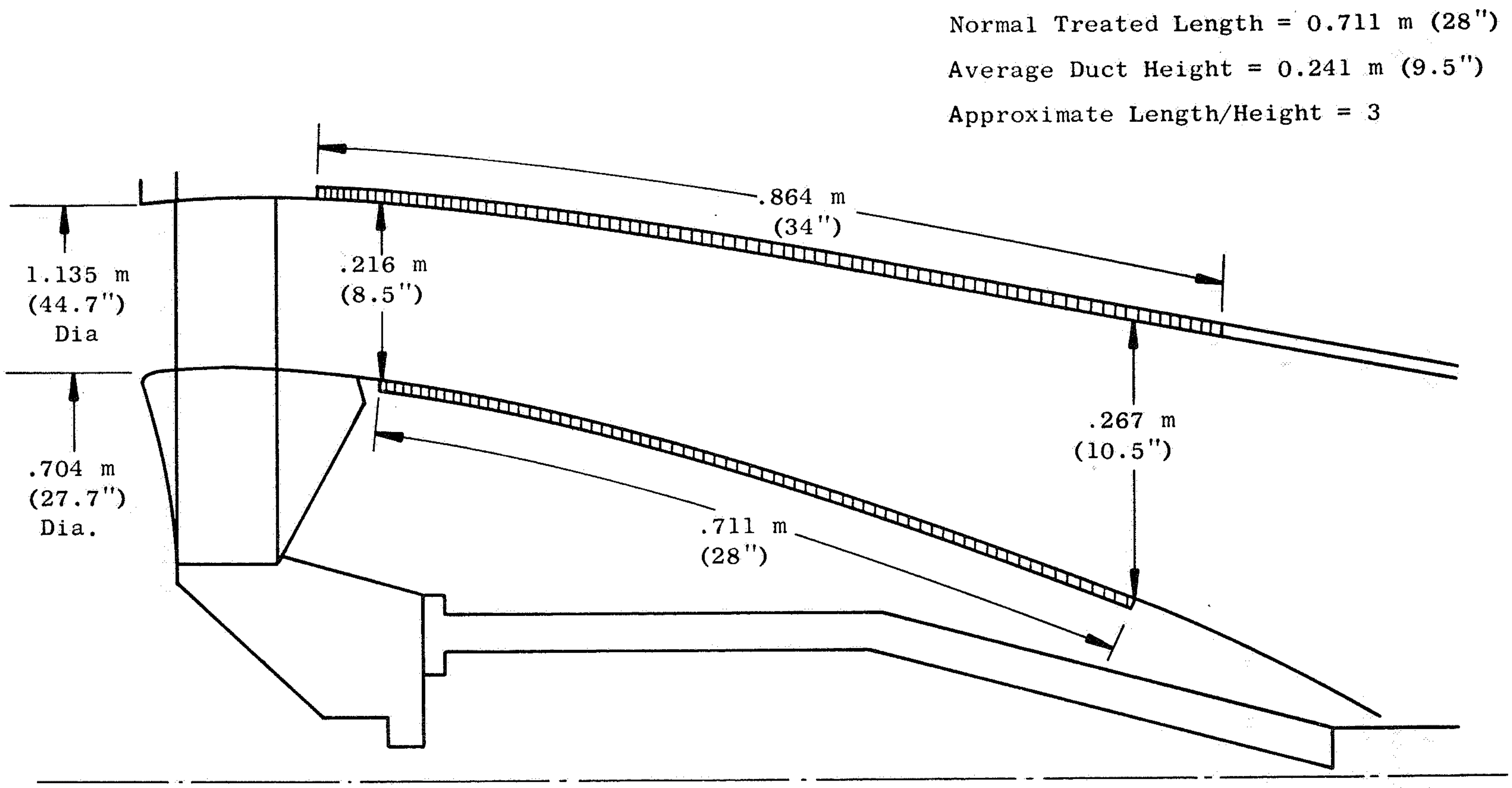


Figure 36. Engine A Acoustically Treated Exhaust Nozzle.

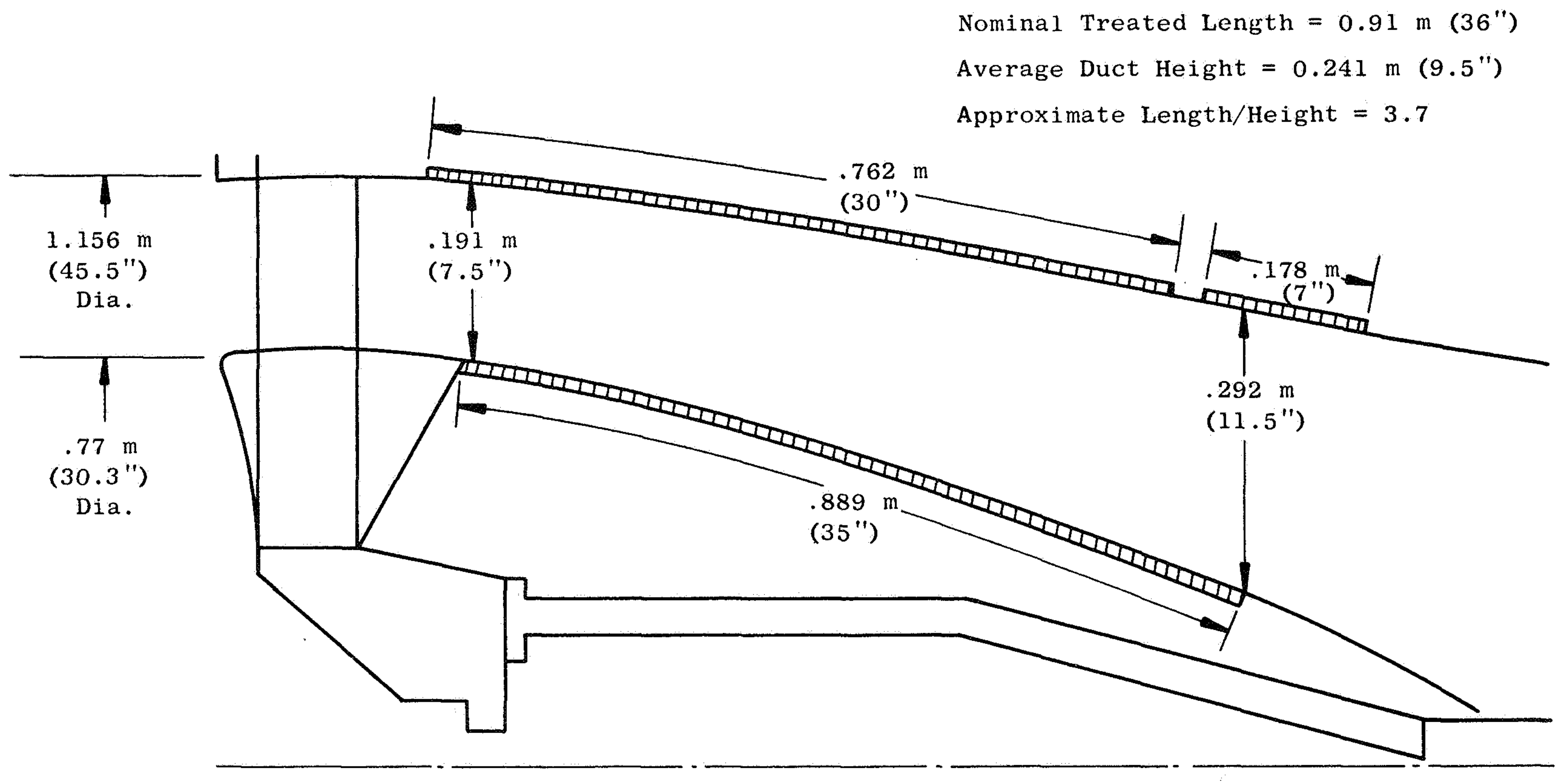


Figure 37. Engine C Acoustically Treated Exhaust Nozzle.

2. Test Configurations

Engines A and C were tested using a nominal core nozzle with various turbine treatment configurations*. The configurations on Engine A consisted of the hardwall baseline and the "Double Sandwich II" resonator system. Engine C testing involved a hardwall baseline, and a SDOF resonator system in the standard nozzle configuration and in a coplanar nozzle configuration. Tests utilizing the probes and the directional acoustic array were conducted at two engine speeds - approach and takeoff - 60% and 90% corrected fan speed, respectively; whereas farfield and nearfield data were recorded at a number of fan speeds (see Section IV.B of this report for standard acoustic test results, as well as configuration descriptions).

3. Acoustic Results

a. "Double Sandwich II" Treatment - Engine A

A summary of treatment effects measured by three methods - probe, directional array, and farfield microphones is shown in Table XVI. The array measurements on the fully treated fan configuration have shown that the fan exhaust-radiated noise (that is, duct noise, fan jet, and core cowl scrubbing noise) dominates the spectra and consequently prevents the measurements of the full turbine treatment effect with farfield data alone on a PNL basis. The measured PNL reduction was in fact only 0.5 PNdB. However, the in-duct acoustic probes showed that the "Double Sandwich II" treatment produced maximum suppression (16.4 dB PWL) at the fourth-stage blade-passing frequency. The directional array in the farfield showed 12 dB fourth-stage tone suppression at the maximum aft PNL angle, and the farfield microphone narrowband data showed suppression to be in excess of 10 dB at this tone. The farfield measurements were limited by a fan-radiated broadband noise floor. Broadband noise reduction was shown, however, to be present from the array measurement, where 6.5 dB suppression was observed in the 1/3-octave band centered on 3150 Hz. Probe broadband data were limited by a duct noise floor.

b. SDOF Treatment - Engine C

In the case of Engine C, a summary of the turbine treatment suppression as measured by probes, nearfield microphones, directional array, and farfield microphones is presented in Table XVII. Probe and directional array data show considerably more suppression at the first stage blade passing frequency than at the second. The second stage tone was not detectable in any farfield measurement, including the array, due to the presence of a noise "haystack" centered at the blade passing frequency. However, the probe data showed that the first stage tone was suppressed on the order of 11 dB and the second stage tone was suppressed on the order of 7 dB.

The directional array data showed that the suppression at the maximum aft angle was 10 dB in both the 4.0 and 5.0 kHz 1/3-octave bands. These suppression

*In both cases the fans were fully suppressed with inlet and exhaust splitters.

Table XVI. Measured Turbine Treatment Suppression on "Fully Suppressed" Engine A at Approach (ΔPNL = 0.5 PNdB).

Stage	Puretones			
	Frequency (kHz)	Probe (ΔPWL, dB)	Directional Array (ΔSPL, dB @ Max. Aft Angle)	Farfield (ΔSPL, dB @ Max. Aft Angle)
4	4.1	16.5	12	>10
3	4.6	12.5	---	>4
2	5.1	13.5	---	---
1	6.1	6.0	2.5	0

Broadband Noise			
1/3 Octave Band	Probe (ΔPWL, dB)	Directional Array (ΔSPL, dB @ Max. Aft Angle)	Farfield (ΔSPL, dB @ Max. Aft Angle)
3150	1.0	6.5	0.5
4000	2.0	4.0	2.0
5000	3.5	2.0	1.5
6300	3.0	---	1.0
8000	1.5	---	-0.5

Table XVII. Measured Turbine Treatment Suppression on "Fully Suppressed" Engine C at Approach (ΔPNL = 4.7 PNdB).

Stage	Puretones			
	Frequency (kHz)	Probe (ΔPWL, dB)	Directional Array (ΔSPL, dB @ Max. Aft Angle)	Farfield (ΔSPL, dB @ Max. Aft Angle)
1	6.0	11.0	13	>7
2	6.5	7.7	>2	>6

Broadband Noise				
1/3 O.B.	Probe (ΔPWL, dB)	Nearfield (ΔSPL, dB)	Directional Array, (ΔSPL, dB @ Max. Aft Angle)	Farfield (ΔSPL, dB @ Max. Aft Angle)
3150	0.5	4.0	7.5	2.5
4000	3.5	5.5	10.0	8.5
5000	5.0	6.5	10.0	8.0
6300	6.0	7.5	8.5	6.5
8000	4.5	6.5	---	3.0

values drop for farfield, nearfield, and probe data (in that order) as the data reach consecutively higher noise floors. Perceived noise level suppression at the maximum aft angle was 4.7 PNdB.

c. Overall Results

A study of the results of the acoustic measurements, in the context of the entire turbine noise suppression program, leads to the following observations:

- A methodology for the design of acoustic treatment and the prediction of noise suppression was developed for turbines, based on acoustic duct, impedance tube, and treated engine configuration test results. The design procedure as developed takes into consideration a series of configurations at temperatures and Mach numbers typical of the turbine region.

- Both metallic and nonmetallic suppression materials were identified for turbine noise suppression applications. Several materials offer improved suppression capabilities, but their application is limited due to installation difficulties and excessive cost.

- Effects of turbine noise suppression cannot be fully realized without substantial fan discharge noise reduction. Engine C, due to its high amplitude of unsuppressed turbine noise and relatively low amplitude of fan noise, permitted large values of farfield suppression to be measured. On the other hand, Engine A turbine treatment resulted in almost negligible farfield PNL suppression due to the presence of a strong fan discharge radiated noise source and relatively low amplitude untreated turbine noise.

- The turbine noise suppression values can be measured by several techniques. Pure tone suppression, however, can only be accurately measured by probes within the core nozzle, since these tones are modulated in the mixing region and do not appear as tones in the near or farfield. Broadband suppression, however, cannot be measured by the probes due to probe self noise and duct flow noise floors. The most satisfactory measurement of broadband suppression utilizes a directional microphone system in the farfield which effectively filters out some of the engine broadband sources.

- Power level suppression on Engine A, as measured by acoustic probes, was seen to range from 6 to 19.5 dB for the turbine tones. The power level suppression on Engine C was seen to range from 7 to 11 dB for the two strongest turbine tones.

Additional information on the turbine noise suppression program is given in Reference 22.

SECTION VI

FLIGHT ENGINE DESIGN STUDY

A. BASIS OF THE FLIGHT ENGINE DESIGN STUDY

One of the objectives of the Experimental Quiet Engine Program was to assess the impact on airline economics of utilizing the technology developed in a modern flight-type engine on CTOL-type aircraft. Accordingly, the flight engine design study was conducted, and included the following elements:

- A preliminary flight engine design incorporating the basic technology features of the Experimental Quiet Engine Program with a modern core. The study included both a low-tip-speed (Fan A derivative) and high-tip-speed (Fan C derivative) engine.
- For each engine, identification of the basic characteristics including size, weight, cost, noise, and performance in a reference untreated (i.e., hardwall) nacelle.
- Establishment of the installed characteristics in a nacelle with varying degrees of noise suppression and evaluating the effect on performance, weight, cost, and noise.
- Evaluation of the impact of the various suppressed engine configurations on the aircraft economics of new tri-jet aircraft.
- Comparison of the effect of noise suppression (ΔEPNdB) on high and low speed fan engines on the aircraft operating costs (ΔDOC) for each engine.

B. ENGINE CHARACTERISTICS

1. Low Speed Engine Characteristics

a. Basic Engine

The low speed engine was derived from the Experimental Quiet Engine Program Fan A, adapted to a modern, properly sized core, and sized for an SLS take-off thrust of 22,000 lb (97,900 N) with nominal installation losses. The primary cycle characteristics are tabulated in Table XVIII. An engine cycle representative of CTOL applications was selected to provide for a mixed core and fan stream ahead of the nozzle. The jet velocity shown in Table XVIII represents the velocity after mixing. A short tabulation of the major fan characteristics is contained in Table XIX. Other engine characteristics are given in Reference 24.

Table XVIII. Flight Engine Design Study, Low Speed Fan Cycle.

Parameter	M = 0, SL Takeoff 86° F (30° C) Day	M = 0.85, 35K Max. Cruise Std + 10° C Day
Thrust, lb (N)	22,000 (97,900)	4950 (22,000)
$W\sqrt{\theta}/\delta$, lb/sec (kg/sec)	830 (377)	993 (450)
Fan Pressure Ratio	1.43	1.49
Bypass Ratio	6.8	6.8
Turbine Rotor (Cycle) Temperature, ° F (° C)	2330 (1277)	2140 (1172)
Core Supercharging Pressure Ratio	2.2	2.5
Core Corrected Flow, lb/sec (kg/sec)	56 (25.4)	58 (26.4)
Overall Pressure Ratio	24	28
Jet Velocity, ft/sec (m/sec)	900 (274)	---

Table XIX. Flight Engine Design Study, Design Summary for Low Speed Fan Engine.

<u>Fan Aero</u> (Cruise)

Diameter, inches (meters)	68.7 (1.74)
Corrected Flow, lb/sec (kg/sec)	933 (424)
Pressure Ratio	1.49
Corrected Tip Speed, Cruise/Takeoff, ft/sec (m/sec)	1160/1060 (354/323)
Corrected Flow/Annulus Area, lb/sec-ft^2 (kg/sec-m^2)	42.3 (207)

The low speed engine fan applies the measured performance characteristics of Fan A in the bypass flow. The cycle pressure ratio was set so as to assure a clean inlet stall margin of 17%, which was considered appropriate to provide stall-free operation in the most severe operational environment anticipated for such an engine. The fan radius ratio was reduced from the Fan A value of 0.465 to 0.4 in the low speed engine. Booster stages were used to provide for the desired core supercharging pressure ratio of 2.5. Five booster stages were selected to meet the requirement of boost pressure ratio plus an adequate stall margin.

The five-stage, low pressure turbine was selected to provide a moderately loaded turbine consistent with design efficiency objectives.

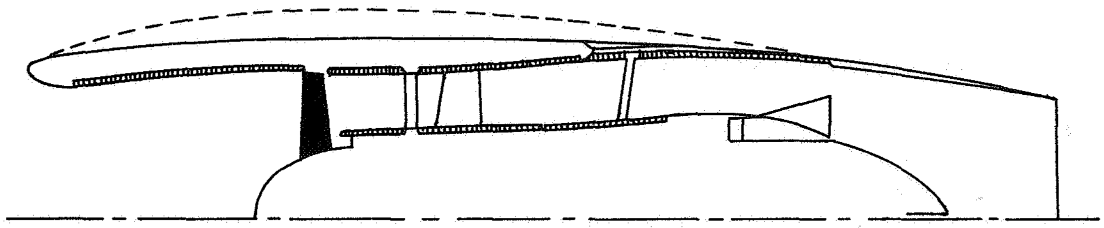
b. <u>Nacelle Configurations</u>

Overall arrangement: The engine was installed in a long-duct nacelle illustrated in Figure 38. The major features are:

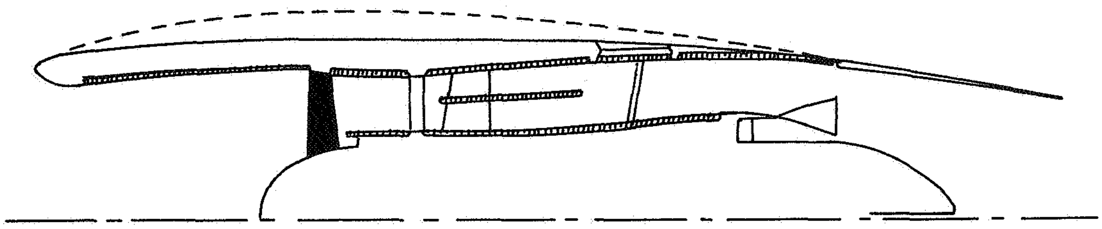
- Mixed core and fan flows. This arrangement provides a thermodynamic advantage with an improved sfc and mixes out the higher velocity core jet to reduce the exhaust jet noise.

- Fan thrust reverser upstream of the mixing plane. Actuation of the fan thrust reverser (closing off the duct upstream of the mixing plane) effectively provides a large increase in the core nozzle area, resulting in a spoiling of the core thrust and eliminating need for a separate thrust reverser.

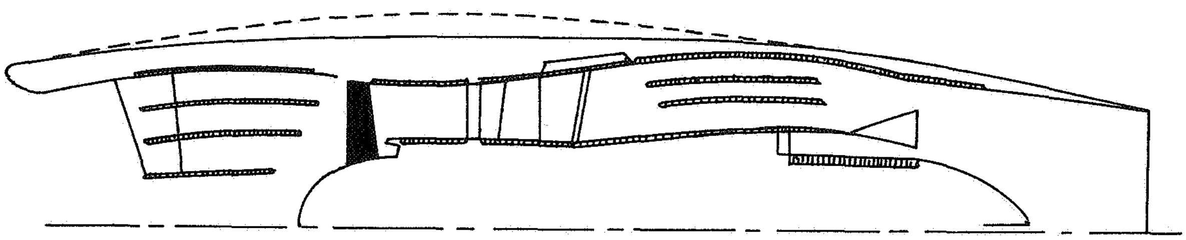
The impact of incorporating various degrees of acoustic treatment was investigated by comparing the following configurations:



a. Wall Treatment



b. Wall Treatment Plus One Aft Splitter



c. Wall Treatment Plus Three Inlet Splitters and Two Aft Splitters Plus Core Treatment

Figure 38. Flight Engine Design Study, Low Speed Engine Treatment Configurations.

- Basic nacelle without treatment
- With wall treatment only
- With wall treatment and single aft splitter
- With wall treatment + 3 inlet splitters + 2 aft splitters

Schematics of these installations are shown in Figure 38. Configuration 38(b) (with single aft splitter) was selected as a baseline since the low speed engine with wall treatment is dominated by aft fan noise, and the major impact on flyover EPNL will be realized by reducing the aft noise constituent. Configuration 38(c) incorporates massive suppression. This arrangement represents the minimum noise level that could be reasonably achieved with this engine and entails significant compromise in the nacelle. The attainment of this minimum noise level requires multiple splitters in both the inlet and the exhaust; their additional weight, cost of manufacture, and pressure losses all combine to produce an undesirable nacelle relative to current aircraft design practice.

Additional information on the low speed engine and its nacelle configurations is given in Reference 24.

2. High Speed Engine Characteristics

a. Basic Engine

The high speed engine was derived from the Experimental Quiet Engine Program Fan C, adapted to a modern core, and sized for an SLS take-off thrust of 22,000 lb (97,900 N) with nominal installation losses. The primary cycle characteristics are tabulated in Table XX. An engine cycle representative of CTOL applications was selected to provide for a mixed core and fan stream ahead of the nozzle. The jet velocity shown in Table XX represents the velocity after mixing. A short tabulation of the major fan characteristics is contained in Table XXI. Other engine characteristics are given in Reference 24.

The high speed engine fan applies the measured performance characteristics of Fan C in the bypass duct modified to a higher-aspect-ratio, tip-shrouded configuration with 46 blades. The fan pressure ratio of 1.55 was selected as a near optimum value for CTOL applications, balancing the installed performance characteristics with a low take-off jet noise level. A clean inlet stall margin in excess of 17% should provide stall-free operation in the most severe operational environment anticipated for an engine of this type. The Fan C radius ratio was retained, with booster stages added to provide the desired core supercharging pressure ratio of 2.5. Three booster stages were selected to meet the requirement of booster pressure ratio plus an adequate stall margin. This selection was based on aerodynamic loadings consistent with the CF6-50 engine booster stages.

A four-stage low pressure turbine was selected to provide turbine loadings consistent with design efficiency objectives.

Table XX. Flight Engine Design Study, High Speed Fan Cycle.

Parameter	M = 0, SL Takeoff 86° F (30° C) Day	M = 0.85, 35K ft (10.67 km) Max. Cruise Std + 10° C Day
Thrust, lb (N)	22,000 (97,900)	4950 (22,000)
$W\sqrt{\theta}/\delta$, lb/sec (kg/sec)	814 (370)	911 (414)
Fan Pressure Ratio	1.47	1.55
Bypass Ratio	6.35	6.4
Turbine Rotor (Cycle) Temperature, ° F (° C)	2330 (1277)	2140 (1172)
Core Supercharging Pressure Ratio	1.6	2.4
Core Corrected Flow, lb/sec (kg/sec)	58 (26.4)	59 (26.8)
Overall Pressure Ratio	24	28
Jet Velocity, ft/sec (m/sec)	920 (280)	---

Table XXI. Flight Engine Design Study, Design Summary For High Speed Fan Engine.

Fan Aero	
Diameter, inches (m)	68.3 (1.74)
Corrected Flow, lb/sec (kg/sec)	911 (414)
Pressure Ratio	1.55
Corrected Tip Speed, Design/Takeoff ft/sec (m/sec)	1550/1440 (472/439) Same T.O. as CF6-6
Corrected Flow/Annulus Area, lb/sec-ft^2 (kg/sec-m^2)	41.8 (204)

b. Nacelle Configurations

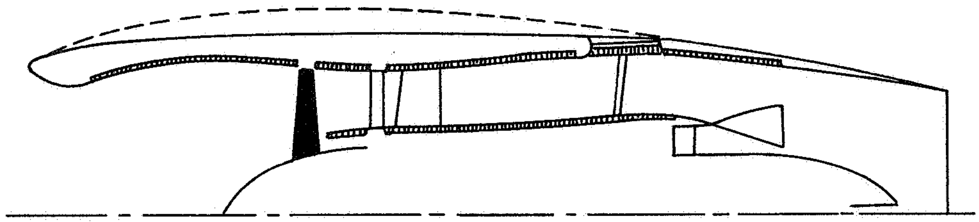
Overall arrangement: The engine was installed in the long-duct nacelle illustrated in Figure 39. As in the low speed engine, the major features are:

- Mixed core and fan flows
- Fan thrust reverser upstream of the mixing plane

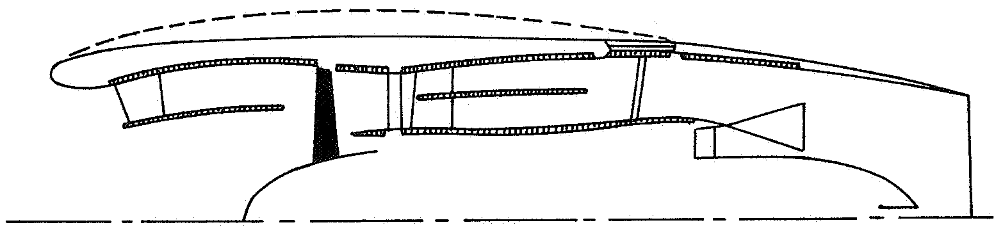
The impact of incorporating various degrees of acoustic treatment was investigated by comparing the following configurations:

- Basic nacelle without treatment
- With wall treatment only
- With wall treatment and single inlet and aft splitters
- With wall treatment + 3 inlet splitters + 2 aft splitters

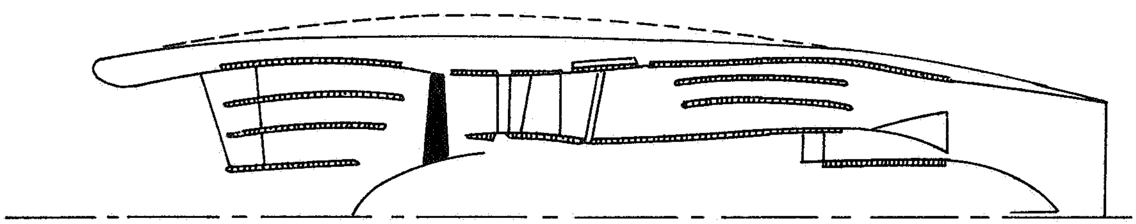
Schematics of these installations are shown in Figure 39. Configuration 39(b) (with single inlet and aft splitters) was selected as a baseline since the high speed engine with wall treatment is nearly balanced between inlet and aft noise at takeoff and, in order to make full impact on flyover EPNL, both fore and aft noise constituents must be reduced. Configuration 39(c) incorporated massive suppression in both fan inlet and exhaust ducts and required turbine noise suppression as well. This arrangement represents the minimum noise level that could be reasonably achieved with this engine and entails significant compromise in the nacelle. The attainment of this minimum noise level requires multiple splitters in both the inlet and the exhaust; their additional weight, cost of manufacture, and pressure losses all combine to produce so undesirable nacelle relative to current aircraft design practice.



a. Wall Treatment



b. Wall Treatment Plus 1 Inlet Splitter and 1 Aft Splitter



c. Wall Treatment Plus 3 Inlet Splitters and 2 Aft Splitters
Plus Core Treatment

Figure 39. Flight Engine Design Study, High Speed Engine Treatment Configurations.

Additional information on the high speed engine and its nacelle configurations is given in Reference 24.

C. AIRCRAFT CHARACTERISTICS

The engine nacelle designs described in Section B were used for aircraft application studies of a tri-jet aircraft. The new tri-jet aircraft was considered adjustable in size and gross weight in order to maintain a fixed payload and range for each engine/nacelle combination.

The baseline aircraft was selected to meet the following criteria:

Payload, lb (kg)	35,400 (16,000)
Number of passengers	177
Range, N.M. (km)	1,850 (3,426)
Wing Loading, W/S, lb/ft^2 (kg/m^2)	104 (510)
Cruise Altitude, ft (m)	30,000 (9,144)
Cruise Mach Number	0.84

The result baseline aircraft characteristics were:

Take-off Gross Weight, lb (kg)	200,500 (90,950)
OWE, lb (kg)	112,000 (50,900)
Avg. Installed Cruise Thrust/Eng, lb/eng (N/eng)	4,560 (20,280)
Static Take-off Thrust/Eng, lb/eng (N/eng)	22,000 (97,900)
Block Time, hour	4.22
Block Speed, N.M./hr (km/hr)	438 (811)

The DOC estimates for this aircraft were obtained using the procedure applied in the ATT studies (Reference 32). The sensitivity factors for the tri-jet were estimated for the case of a constant payload and mission. The base aircraft and engines were scaled for changes in sfc and pod weight. The cost effects of scaling the aircraft size are included in the overall DOC sensitivity factors. The resultant sensitivity factors for the major engine and nacelle characteristics are:

FACTOR	Δ% DOC*	Δ% TOGW
1 % total Δsfc	0.55	0.66
100 lb Δ Pod Weight (each)	0.26	0.36
$10,000 Δ Engine Price	0.26	---
$10,000 Δ Nacelle Price	0.15	---
* Δ% DOC also includes change in DOC due to change in aircraft size.		

Additional information on the tri-jet CTOL aircraft and its economic factors is given in Reference 24 .

D. FLIGHT NOISE PROJECTIONS

1. Prediction Procedure

The noise characteristic produced at a ground measurement point by an aircraft flyover along a given flight path was estimated using the following procedure:

- The engine noise sources were approximated by substituting the predicted ground static data at 10° angle increments to the engine inlet.
- At a given instant in time the range from the ground observer to the moving aircraft was determined as a function of angle to the inlet axis.
- The engine data were interpolated to match the flyover acoustic angle.
- Correction factors were applied to the static data depending on separation distance and aircraft velocity. These correction factors were (1) the spherical divergence dissipation of sound energy, (2) the atmospheric absorption as specified in SAE Specification ARP 866 (Reference 33), and (3) a ground boundary attenuation as specified in SAE Specification AIR 923 (Reference 34). The ground boundary layer or EGA factor was further modified by General Electric with the assumption that it applies only in a layer below a 100-ft (30.48-m) altitude. Noise transmission above a 100-ft (30.48-m) altitude was not attenuated with EGA.
- The jet noise was modified to account for the effect of the motion of the aircraft (relative velocity effect).
- Frequency was shifted to account for the Doppler effect.

A computer program was prepared to perform the flyover calculations. The program solves the complex geometry of an aircraft traversing a selected path with varying engine angles and frequencies and results in a flight noise spectrum. This spectrum was then projected over the appropriate acoustic range with the necessary corrections for preparation of a spectrum at the ground position desired. From this predicted spectrum PNL and PNLT values were calculated. This information was then used to calculate an EPNL value for the flyover event as specified in FAR-36. However, the 90 EPNdB floor of the current regulation was not used in this study.

2. Results of Flight Noise Projections

Table XXII shows the results of the flight noise projections. The take-off altitude of this tri-jet was 1600 ft (488 m) and the approach power setting was 34%. Complete aircraft flight path data are given in Reference 24.

As can be seen in Table XXII. both high and low fan speed engines met the FAR-36 requirements in a treated-wall nacelle configuration, and were significantly below the FAR-36 requirements in the "fully-suppressed" nacelle.

Table XXII. Flight Engine Design Study, Predicted EPNL Relative to FAR-36 for Tri-Jet CTOL Transport.

(FAR-36 Take-off and Approach Certification Conditions)

Nacelle Configuration	Key to Figure 40	High Speed Engine		Low Speed Engine	
		Takeoff	Approach	Takeoff	Approach
Hardwall	A	103.1	106.9	97.0	99.0
Treated Wall	B	97.8	99.6	93.5	94.5
Treated Wall + 1 Inlet Splitter + 1 Aft Splitter	C	95.2	96.0	---	---
Treated Wall + 1 Aft Splitter	D	---	---	92.5	93.0
Treated Wall + 3 Inlet Splitters + 2 Aft Splitters	E	91.4	91.0	89.0	87.5
FAR-36	---	100	105	100	105

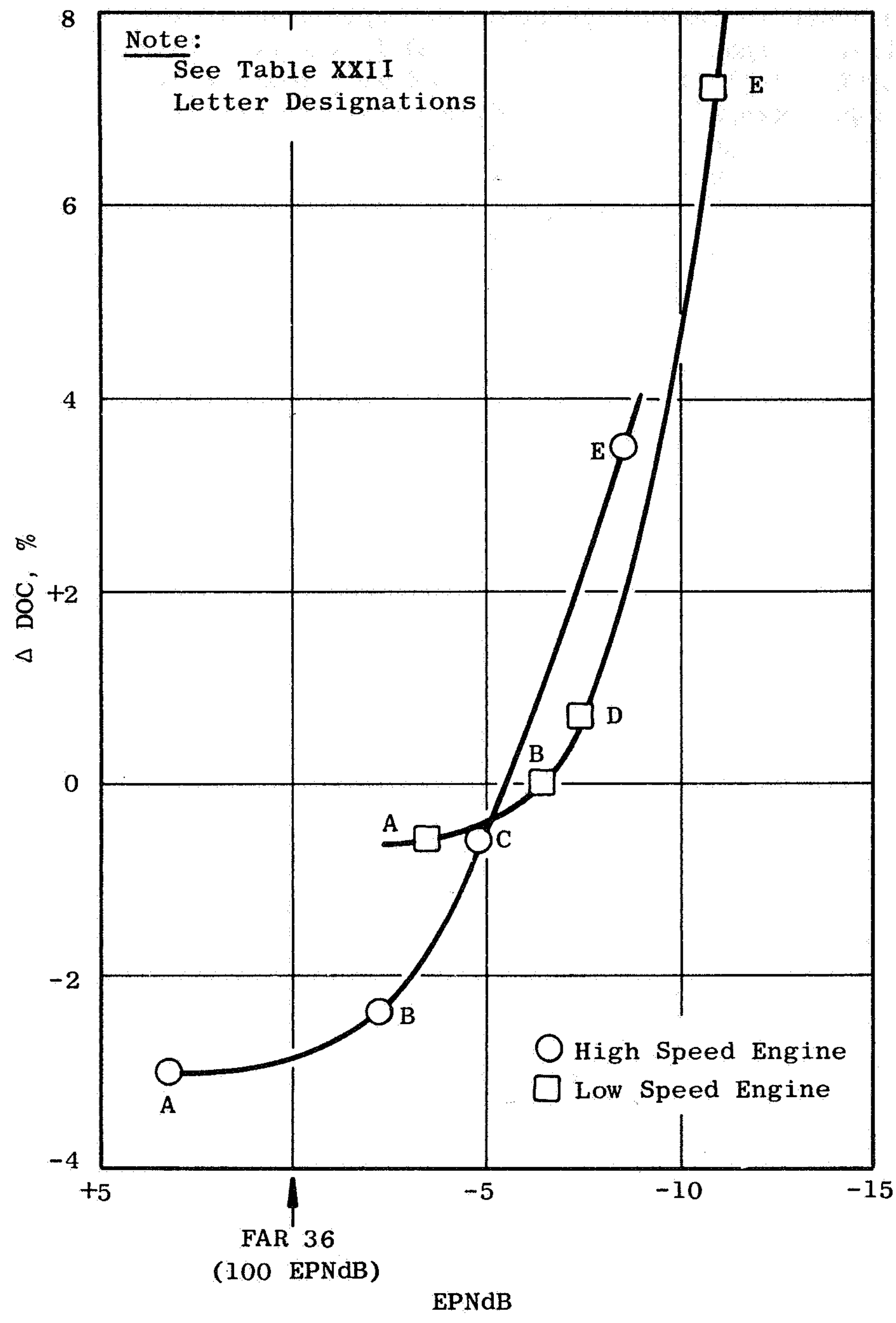


Figure 40. EPNL/DOC Relationship (Takeoff, No Cut-Back, Untraded) for Flight Engine Design Study Engines.

E. ACOUSTICS/ECONOMICS TRADEOFFS

Using the acoustic technology from the Experimental Quiet Engine Program in the preliminary flight engine designs and in the acoustically treated nacelles in a typical CTOL tri-jet transport resulted in projected noise levels well below FAR-36 requirements. The EPNL/DOC relationship determined in the preliminary flight engine design study is shown in Figure 40. The economic penalty associated with the maximum feasible noise reduction (fully suppressed nacelles) is significant. Using the low speed engine in a treated-wall nacelle as the base (present technology) the differential effects on the Direct Operating Cost (DOC) of a typical tri-jet CTOL transport were estimated for the various engine/nacelle configurations, as follows:

DOC Comparison, Tri-Jet CTOL Transport [200,500 lb (90,950 kg) TOGW]

Configurations	High Speed Engine	Low Speed Engine
Hardwall	-3.0%	-0.6%
Treated Wall	-2.4%	Base
Treated Wall +1 Inlet Splitter +1 Aft Splitter	-0.6%	---
Treated Wall +1 Aft Splitter	---	+0.7%
Treated Wall +3 Inlet Splitters +2 Aft Splitters	+3.5%	+7.2%

Considering both noise and DOC effects, at full power take-off noise levels between FAR-36 and FAR-36 minus 5 EPNdB, with a typical tri-jet CTOL transport, a high speed engine in a treated wall nacelle appears to be the most economically attractive. As can be seen on Figure 40, the high speed engine yields a greater noise reduction than the low speed engine for similar nacelle noise reduction features. For significant noise reductions below about FAR-36 minus 5 EPNdB, the cost increases for both low and high speed engines. For noise levels below approximately FAR-36 minus 5 EPNdB to FAR-36 minus 7 EPNdB, the lower source noise of the low speed engine begins to dominate, and (on a DOC basis), appears more economically attractive. Technology being developed since the conduct of the preliminary flight engine design study and future developments may change the above relationships.

Additional information on the flight engine design study is given in Reference 24.

SECTION VII

SUMMARY OF RESULTS

A. ENGINE AND COMPONENT DESIGN

The NASA/General Electric Experimental Quiet Engine Program was initiated in July, 1969 with the objective of developing engine noise reduction technology and demonstrating in engine tests the integrated impact of this technology on reduction of engine noise. A further objective was to determine the impact on airplane economics resulting from the noise control measures required.

The salient results of the Phase I engine and component design effort were as follows:

- The design of three full-scale fans, each containing low noise design features and spanning a range of tip speed and aerodynamic loading of interest.
- The design of three turbofan engines, based on the three fan designs, the TF39/CF6 core, and selected low pressure turbines.
- Selection of inlets for testing, including standard bellmouths, as well as flight-type inlets (thick-lip and thin-lip types). The inlet and exhaust systems were designed to be representative of typical aircraft applications.

B. FULL-SCALE FAN TESTING AND EVALUATION

The three full-scale fan designs were tested aerodynamically as fans alone over the operating range of speed, flow, and pressure ratio with both smooth and distorted inlet flow conditions. Measured levels of weight flow, adiabatic efficiency, and operating margin demonstrated that the fans were satisfactory for use in the overall program.

The three fans were tested acoustically at NASA as fans alone, furnishing acoustic comparisons between Fans A and B which were used in the selection of Engine A as the lower fan tip speed engine. Early information on the acoustic characteristics of Fan C was provided and used in the design of Engine C acoustic treatment. The acoustic characteristics of Fans A and C were compared to engine test results to aid in evaluation of the contribution of the fan component to the overall engine noise levels.

C. HALF-SCALE FAN TESTING AND EVALUATION

The salient results of the program of testing Half-Scale Fans B and C were as follows:

- Investigations with circumferentially leaned outlet guide vanes showed that lean can be used to reduce the noise of low tip speed fans, but that the situation is unclear in the case of high tip speed fans.

- The nacelle treatment investigations with the high speed fan showed that with full nacelle treatment, the inlet suppression is more effective at takeoff than at approach, while the converse is true for the aft duct treatment.

- Investigations of rotor blade modifications of the high speed fan showed that a change in the basic airfoil design criteria can act to reduce multiple pure tone (MPT) noise in fans with supersonic blade relative Mach numbers. Future design changes aimed at reducing MPT's must acknowledge the possibility that the blade passing frequency noise will increase.

- The inlet suppression investigations with the high speed fan showed that multiple acoustically treated splitters and a high average inlet throat Mach number result in appreciable take-off noise reduction, although inlet recovery is penalized. Reduction of the number of splitters in this case slightly improves both acoustic and aerodynamic performance. The best ratio of recovery loss to Perceived Noise Level (PNL) reduction was shown by a high-Mach-number inlet with an acoustically treated cowl without splitters. Noticeable flow acceleration effects on noise start to appear at Mach numbers ≥ 0.65.

D. ENGINE TESTING AND EVALUATION

Engine testing was conducted on a low-fan-speed engine (A) and a high-fan-speed engine (C). In the case of Engine A, the following features were investigated: fan frame acoustic treatment, core engine exhaust treatment, engine inlet designs, duct splitter treatment, engine casing wrapping, and engine operating line (various exhaust nozzle sizes). The salient results of the Engine A acoustic testing were as follows:

- At low power settings, overall engine noise levels could be reduced by moving to lower operating lines.

- The bellmouth inlet produced lower noise levels than either of the flight inlets tested. The thick-lip flight inlet was quieter than the thin-lip, blow-in-door inlet operating with doors fixed open.

- Engine casing noise radiation was insignificant.

Based on the projection of Engine A static acoustic test results to in-flight conditions, the predicted noise levels of representative older four-engine aircraft powered by four A-type engines with duct wall treatment showed noise reductions of more than 20 effective perceived noise decibels (EPNdB) relative to current older aircraft and 8 EPNdB relative to FAR-36*. Further, the Engine-A-powered aircraft in the "fully-suppressed" configuration showed projected noise levels which were more than 25 EPNdB below those of the current older aircraft and more than 13 EPNdB below FAR-36.

*Federal Aviation Regulations, Part 36, December, 1969.

Aerodynamic performance testing of Engine A showed that the engine had satisfactory aero/thermodynamic performance. General agreement was found between full-scale engine performance and full-scale fan performance from the component test results. Satisfactory engine operation was demonstrated with both thick-lip and thin-lip (blow-in-door) flight inlets.

In the case of Engine C, the following features were investigated: fan frame acoustic treatment, treated inlet designs, duct splitter treatment, core engine exhaust treatment, coplanar exhaust nozzles, and engine operating line (various exhaust nozzle sizes). The salient results of the Engine C acoustic testing were as follows:

- Noise levels similar to those attained with suppressed, lower-tip-speed fan engines can be achieved with suppressed, higher-tip-speed fan engines.

- Multiple pure tone (MPT) noise can be effectively suppressed (although not completely eliminated).

- Fan exhaust noise was suppressed to the extent that turbine/core-related noise controlled the aft noise levels at approach power setting.

- The relative axial positions of the fan and core jet exhaust planes can significantly influence the characteristics of the low pressure turbine blade passing frequency tones which are radiated to the far field.

Based on the projection of Engine C static acoustic test results to in-flight conditions, the predicted noise levels of representative older four-engine aircraft powered by four C-type engines with duct wall treatment showed noise reductions of more than 20 effective perceived noise decibels (EPNdB) relative to current older aircraft and 8 EPNdB relative to FAR-36. Further, the Engine-C-powered aircraft in the "fully-suppressed" configuration showed projected noise levels which were more than 24 EPNdB below those of the current older aircraft and more than 12 EPNdB below FAR-36.

Aerodynamic performance testing of Engine C showed that the engine had satisfactory aero-thermodynamic performance. General agreement was found between full-scale engine performance and full-scale fan performance from the component test results.

E. TURBINE NOISE SUPPRESSION PROGRAM

In the turbine noise suppression program, high temperature acoustic treatment was developed for the core engine exhaust of Engines A and C. Special tests were performed on both engines to evaluate suppression of the low pressure turbine blade passing frequency tones and broadband noise. The salient results of this investigation were as follows:

- A methodology for acoustic treatment design and noise suppression prediction was developed for turbines.

- Metallic and other treatment materials were identified for potential use in core exhaust suppression.

- Turbine noise suppression can be measured by several techniques, the most satisfactory being core nozzle probes for tone noise, and a directional farfield microphone system for broadband noise.

F. FLIGHT ENGINE DESIGN STUDY

Two preliminary flight engine designs were made, incorporating the basic noise reduction and aerodynamic features of Fans A and C, as well as a modern core engine sized to produce 22,000 lb (97,900 N) sea level static thrust. The size, weight, cost, noise, and performance characteristics for the two engines were evaluated as applied to a modern Conventional Take-off and Landing (CTOL) tri-jet having 200,500 lb (90,950 kg) take-off gross weight, in order to determine the economic impact (in terms of direct operating cost) of engines designed with high- or low-tip-speed fans and with varying amounts of noise suppression.

The salient results of this program were as follows:

- Aircraft powered by both high- and low-fan-speed flight engines met FAR-36 requirements in treated-wall nacelle configurations, and were significantly below FAR-36 with "fully-suppressed" nacelles.

- The economic penalties associated with the maximum feasible noise reductions ("fully-suppressed" nacelles) were significant.

- Considering both noise and economic effects at full-power take-off noise levels between FAR-36 and FAR-36 minus 5 EPNdB, high-speed-fan engines in treated wall nacelles appeared to be the most economically attractive.

- The high-speed-fan engine showed greater noise reductions than the low-speed-fan engine for similar nacelle noise reduction features.

- For significant noise reductions below about FAR-36 minus 5 EPNdB, the cost increased for both low- and high-fan-speed engines. For noise levels below approximately FAR-36 minus 5 EPNdB to FAR-36 minus 7 EPNdB, the lower source noise of the low-fan-speed engine begins to dominate, and the low-fan-speed engine appeared more economically attractive. Technology being developed since the conduct of the preliminary flight engine design study and future developments may change the above relationships.

APPENDIX - LIST OF SYMBOLS

I. Symbol	Definition	Units
A	Area	in.^{2}, ft^2 (cm^2, m^2)
	Centerline (mechanical)	---
CTOL	Conventional Takeoff and Landing	---
D	Diameter	in. (cm)
DOC	Direct Operating Cost	\$/hr
EPNL	Effective Perceived Noise Level	EPNdB
F	Thrust (as in F_n)	lb (N)
FAR	Federal Aviation Regulations	---
FOD	Foreign Object Damage	---
g	Acceleration of Gravity	ft/sec^2 (m/sec^2)
H, h	Height	in. (cm)
h	Enthalpy	Btu/lb (Joules/kg)
HP	High Pressure (as in HP Turbine)	---
J	Mechanical Equivalent of Heat	ft lb/Btu $(\frac{m\ N}{joules})$
LP	Low Pressure (as in LP Turbine)	---
M	Mach Number	---
MDOF	Multiple Degree of Freedom (acoustic treatment design)	---
MPT	Multiple Pure Tone (Acoustic-Series of Per-Rev Pure Tones	---
N	Number (as in N_V, number of vanes)	---
N	Rotational Speed	rpm
O.B.	Octave Band (acoustic)	---
OGV	Outlet Guide Vane	---
OWE	Operating Weight, Empty	lb (kg)

APPENDIX - LIST OF SYMBOLS (Cont'd)

Symbol	Definition	Units
P	Pressure	lb/in.^{2} (N/m^2)
PNL	Perceived Noise Level	PNdB
P.S.	Power Setting	percent thrust
PWL	Power Level (Acoustic)	dB re 10^{-13} watts
R-THETA	Circumferential Distance Coordinate of Blade Design	in. (cm)
S	Wing Surface Area	ft^2 (m^2)
SDOF	Single Degree of Freedom (acoustic treatment design)	---
sfc	Specific Fuel Consumption (fuel flow per unit thrust)	hr^{-1}
SLS	Sea Level Static - Sea Level Altitude, Zero Mach Number	---
SPL	Sound Pressure Level (acoustic)	dB re 0.0002 d/cm^2
T	Temperature	°F, °R (° C, ° K)
T/O	Takeoff	---
U	Velocity (rotating machinery design)	ft/sec (m/sec)
V	Velocity (aircraft, etc.)	ft/sec (m/sec)
W	Weight Flow (aerodynamic)	lb/sec (Kg/sec)
W	Weight (aircraft design)	lb/ (Kg)
Z	Axial Distance Coordinate of Blade Design	in. (cm)
Δ	Delta - Difference, Increment	(same as basic unit)
δ	Corrected Pressure: P/P_{ref} where P_{ref} = ISO standard sea level pressure	---
η	Efficiency, as in η_{Ad}	---

Symbol	Definition	Units
η	Recovery, as in η_r	---
θ	Corrected Temperature; T/T_{ref} where T_{ref} = ISO standard sea level temperature	---

II. Subscripts

Subscripts	Definition
Ad	Adiabatic, as in η_{Ad}
B	Blade, as in N_B (number of blades)
f	Fan, as in N_f (fan speed)
HL	Highlight, as in D_{HL}
Max.	Maximum
Min.	Minimum
n	Net, as in F_n (net thrust)
P	Pitchline, as in U_p (pitchline velocity of blade)
r	Inlet ram pressure recovery, as in η_r
T	Total (pressure), as in P_T
TH	Throat
V	Vane, as in N_V (number of vanes)

III. Engine Station Location

2	Fan Inlet
2C	Core Inlet
23	Fan Outlet (bypass region)
24	Fan Outlet (core region)
3.9	Combustor Outlet
4	High Pressure Turbine Inlet
54	Low Pressure Turbine Inlet
56	Low Pressure Turbine Outlet

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